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U.S. DEPARTMENT OF ENERGY

OpenPET User Meeting: Status and Update

Woon-Seng Choong, Faisal Abu-Nimeh, Jennifer Huber, William Moses, Qiyu Peng

November 14, 2014

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Agenda

- **Status and Update – Woon-Seng Choong (20 min)**
- **Work at University of Manitoba – Andrew Goertzen (10 min)**
- **Work at Rush University – Kosta Popovic (10 min)**
- **Work at UC Davis – Martin Judenhofer (10 min)**
- **Q & A**

Outline

- Introduction
- Hardware Status
- Firmware and Software Status
- New Improved Website

OpenPET Vision

Open Source

- Hardware, Firmware, and Software
- Schematics, Gerbers, BOM,…

Standardized Architecture

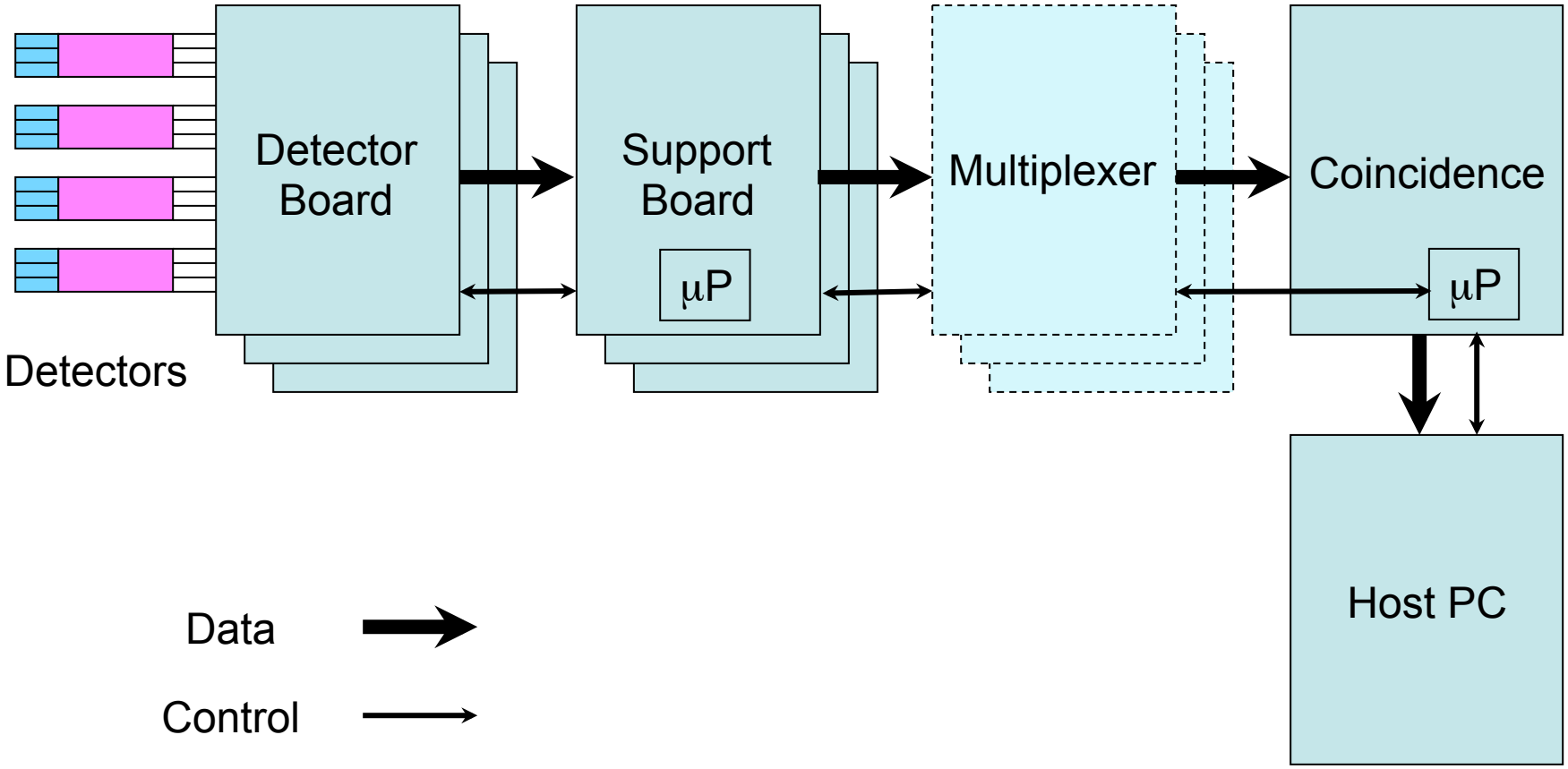
- High-Performance, Flexible, Scalable
- Software Readily Transportable

Active User Community

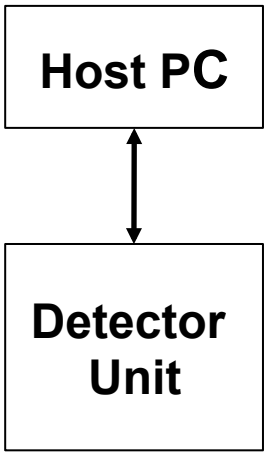
- Share Software and Expertise
- Module, Calibration, DAQ, Display…

OpenPET is the GATE of Nuclear Medical Imaging Electronics

OpenPET Hardware Architecture

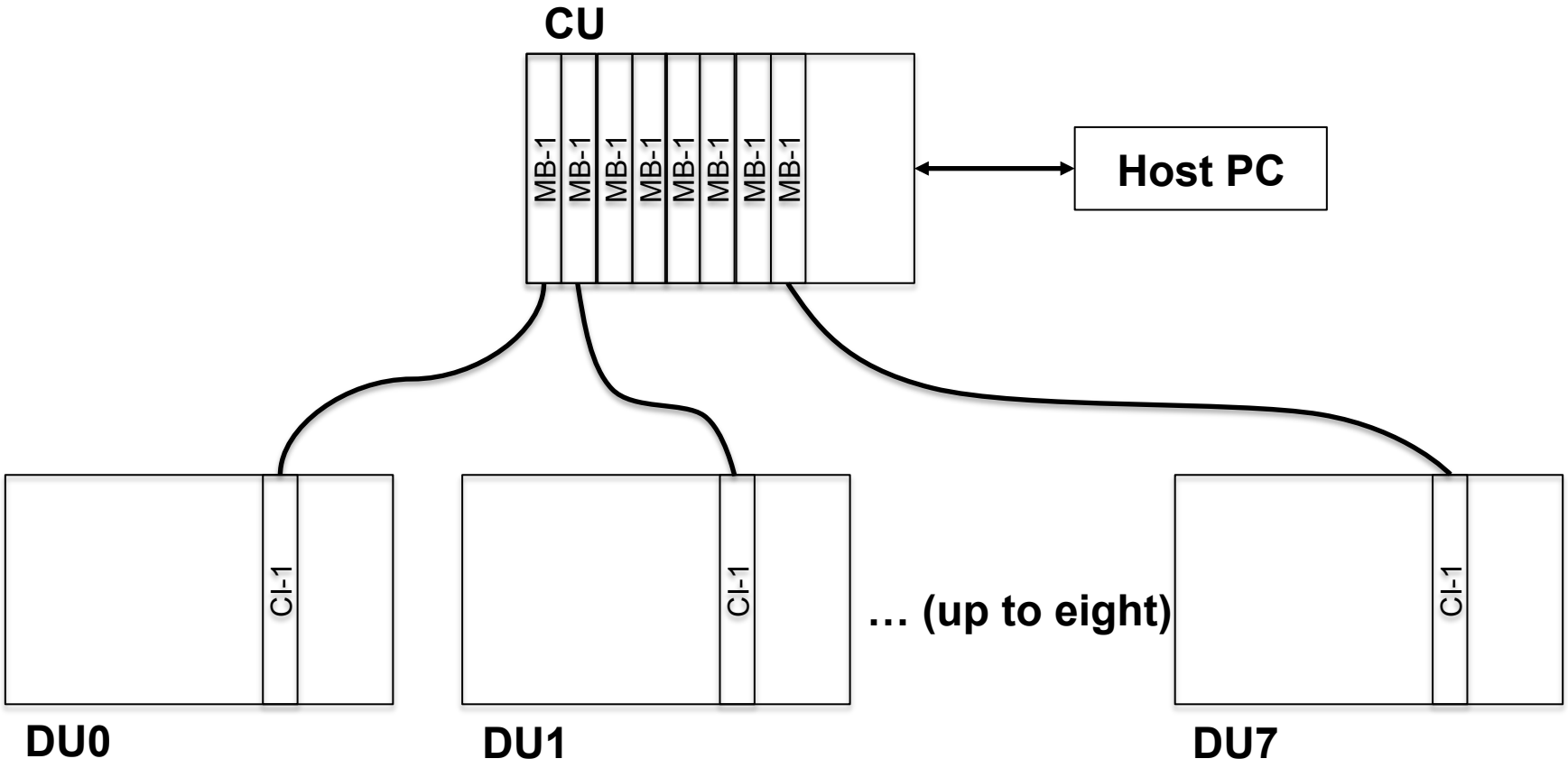


Small System



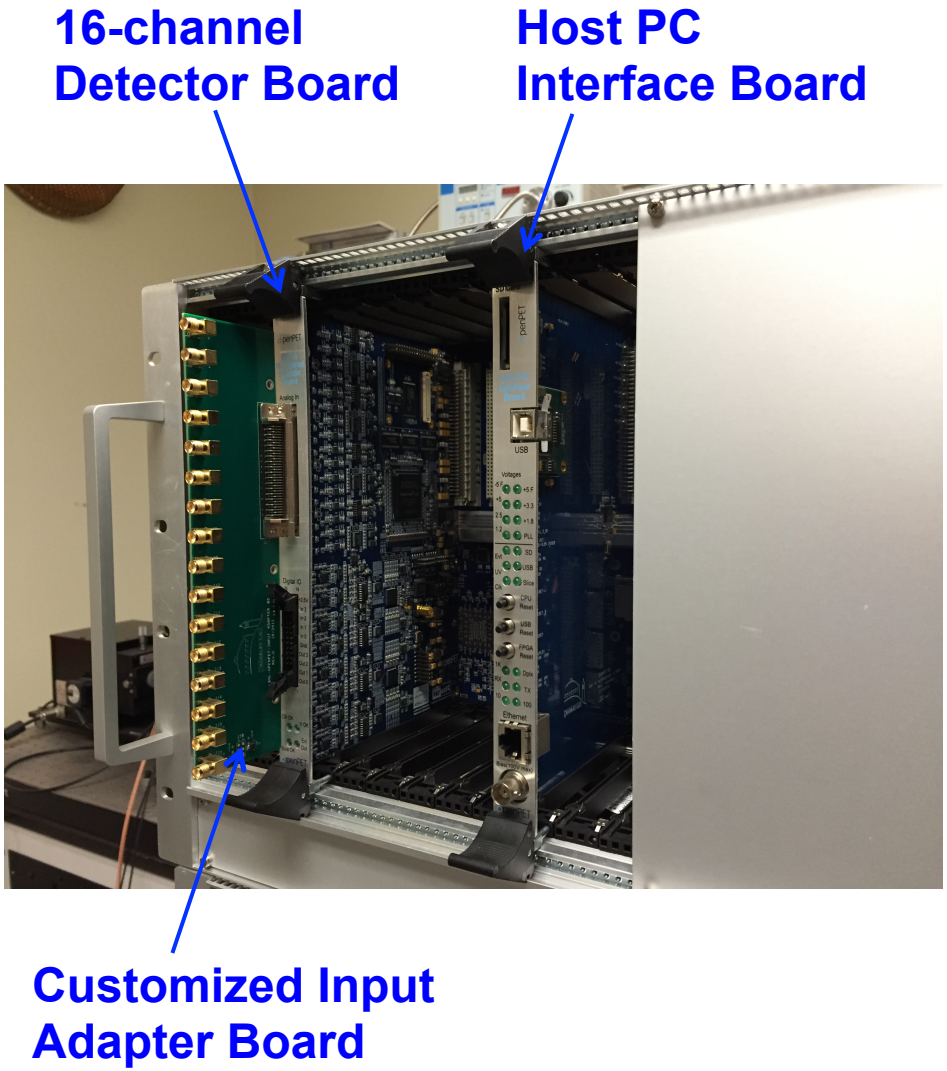
- 1 Support Crate, Up To 8 Detector Boards
- Up to 256 Analog Inputs (64 Block Detectors)
- PC Interface Board Connects to PC

Standard System



- Up To 8 Detector Units, 1 Coincidence Units
- Up to 2048 Analog Inputs (512 Block Detectors)
- Coincidence Interface Board Connects to CU

OpenPET Hardware (v1.0): Small System



OpenPET Hardware (v1.0): Getting Started

For a minimum small system

- One Support Board.
- One 16-Channel Detector Board
- One VME chassis

Additional required hardware

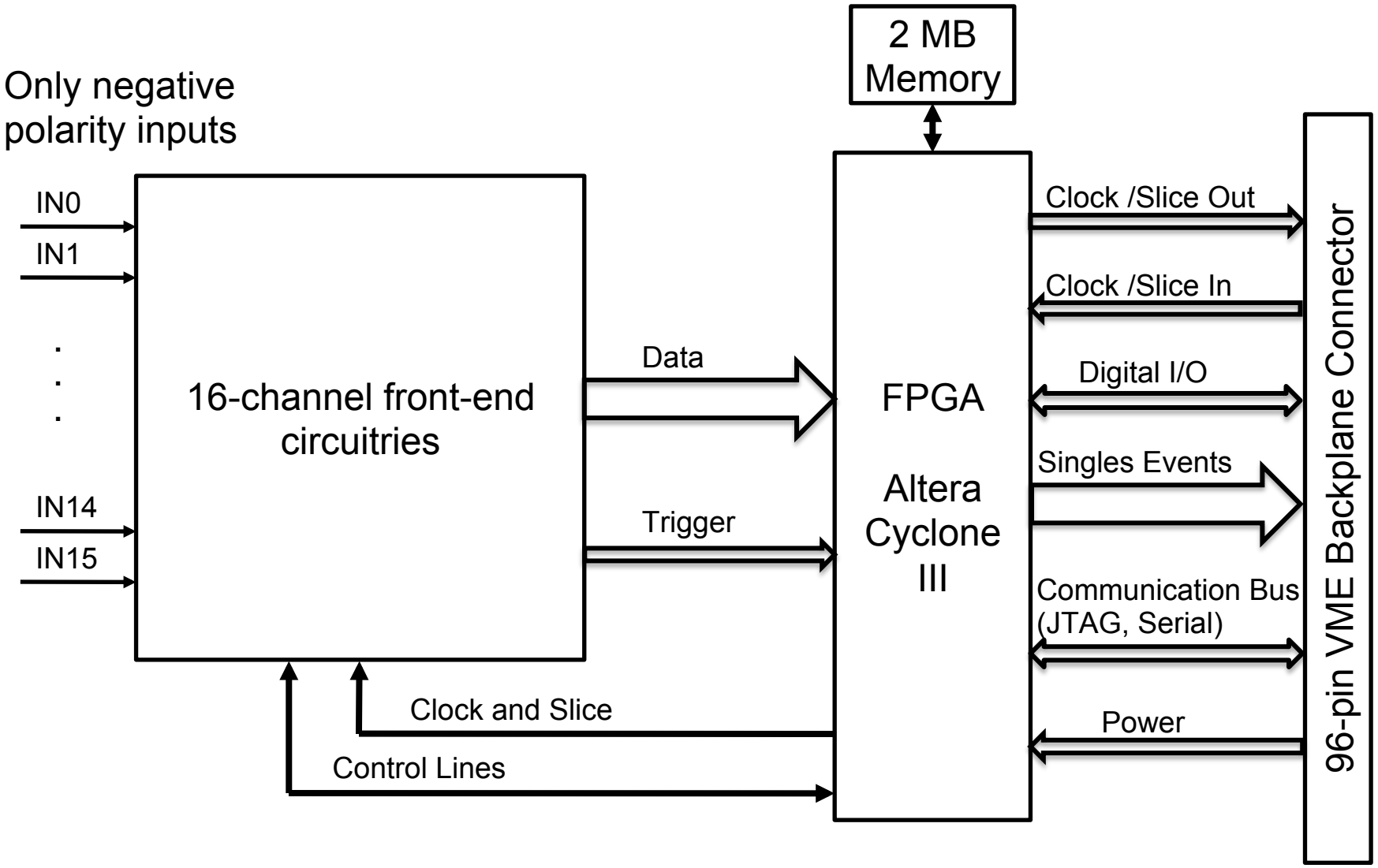
- QuickUSB module: Bitwise Systems, part number QUSB2
- USB-Blaster Cable: Terasic, Digi-Key part number P0302-ND

- **All electronics boards can be purchased through Terasic (http://www.openpet.terasic.com)**
- **VME chassis can be purchased through Elma.**

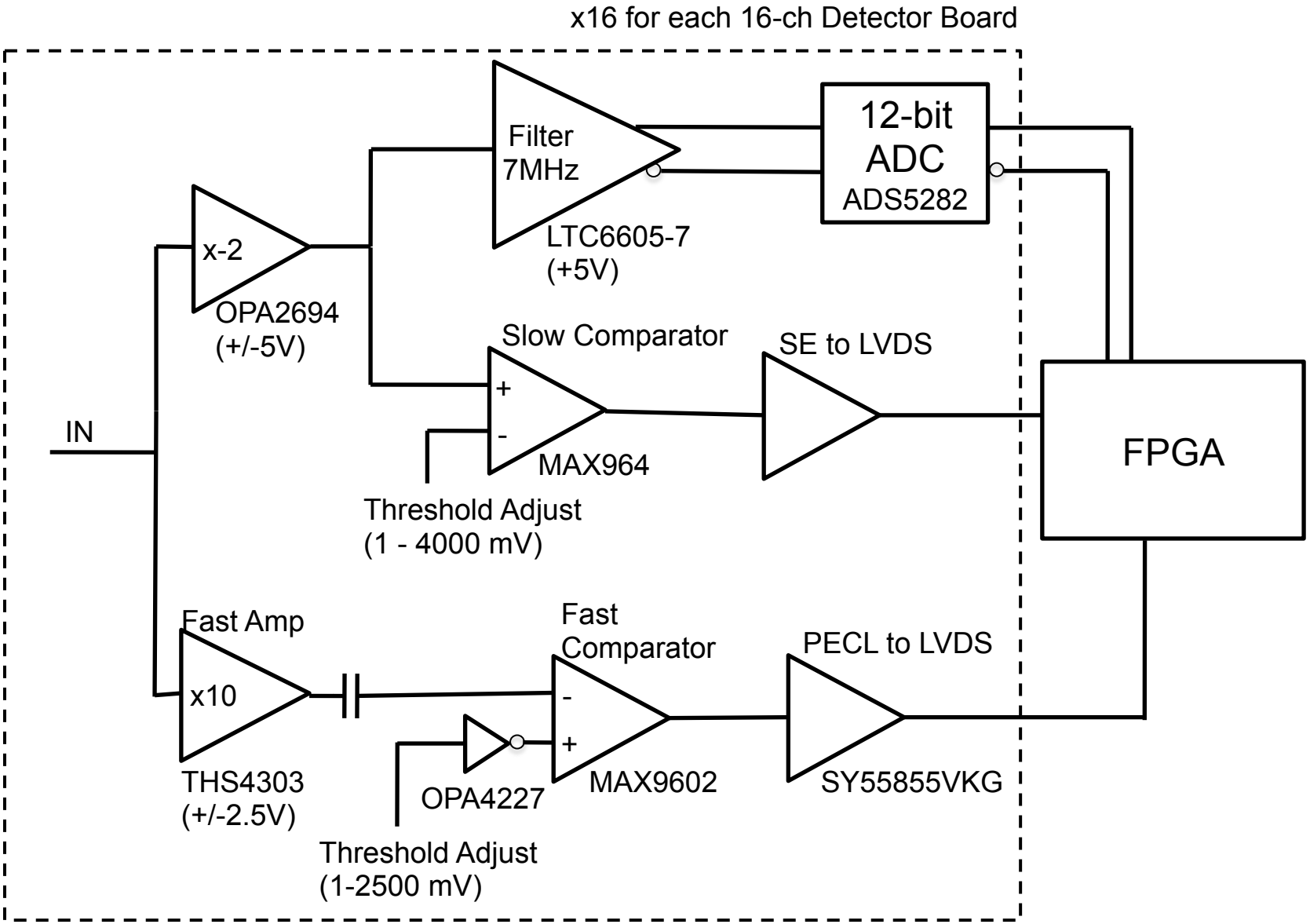
Detector Boards

- **16-Channel Detector Board**
  - Available for purchase from Terasic.
- **32-Channel Detector Board (based on conventional design)**
  - Design is complete (see poster M19-15).
  - Layout is in progress.
- **32-Channel Detector Board (based on DRS4)**
  - Design to start next year.
  - Expect to be available in 1-2 years.

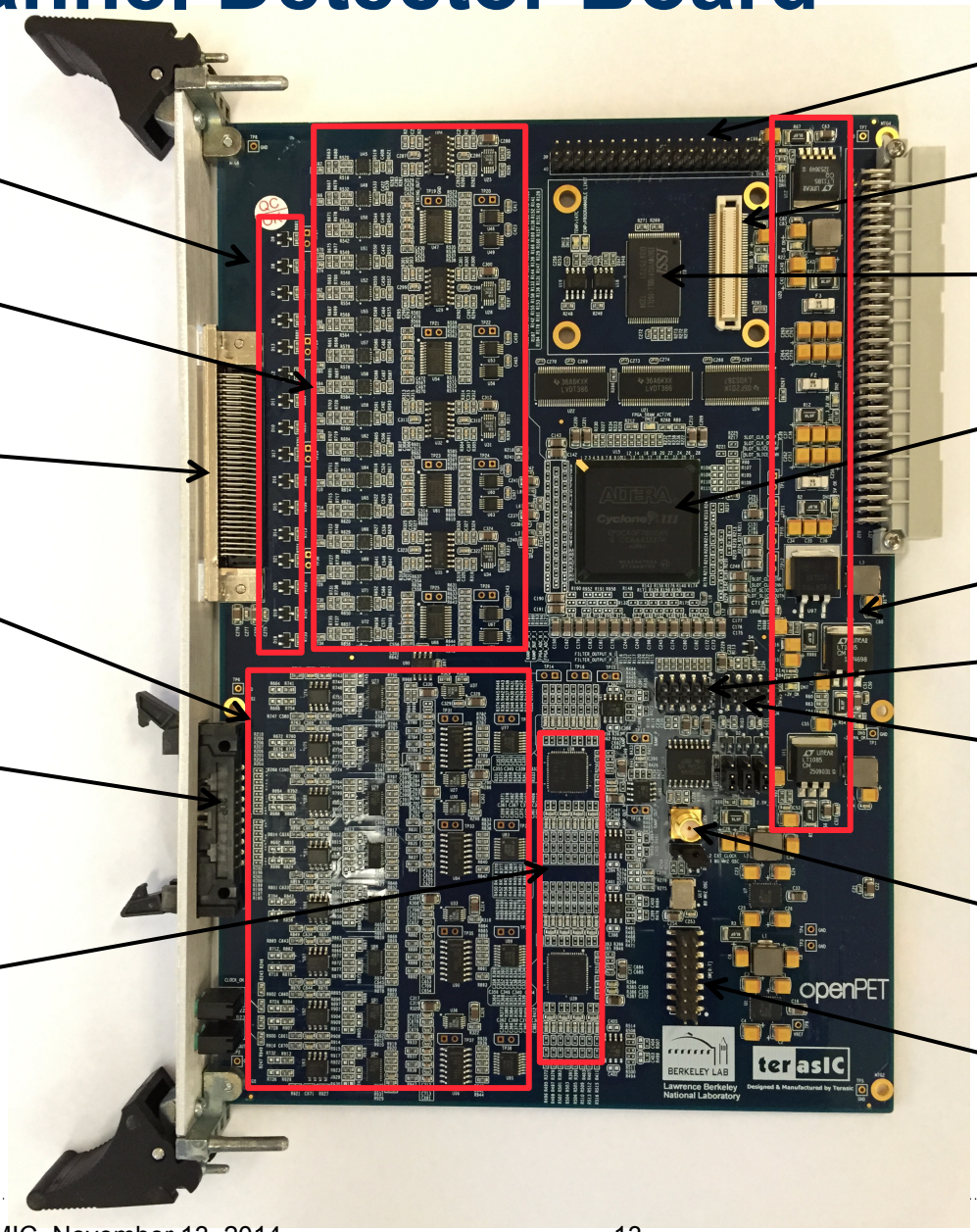
16-Channel Detector Board



16-Channel Detector Board



16-Channel Detector Board



Input Termination

16-channel Timing Chain

Analog Input Connector

16-channel Energy Chain

Digital I/O

ADC

Logic Analyzer Connector

QUSB Connector

2 MB SRAM

FPGA (Cyclone III)

Power Regulator

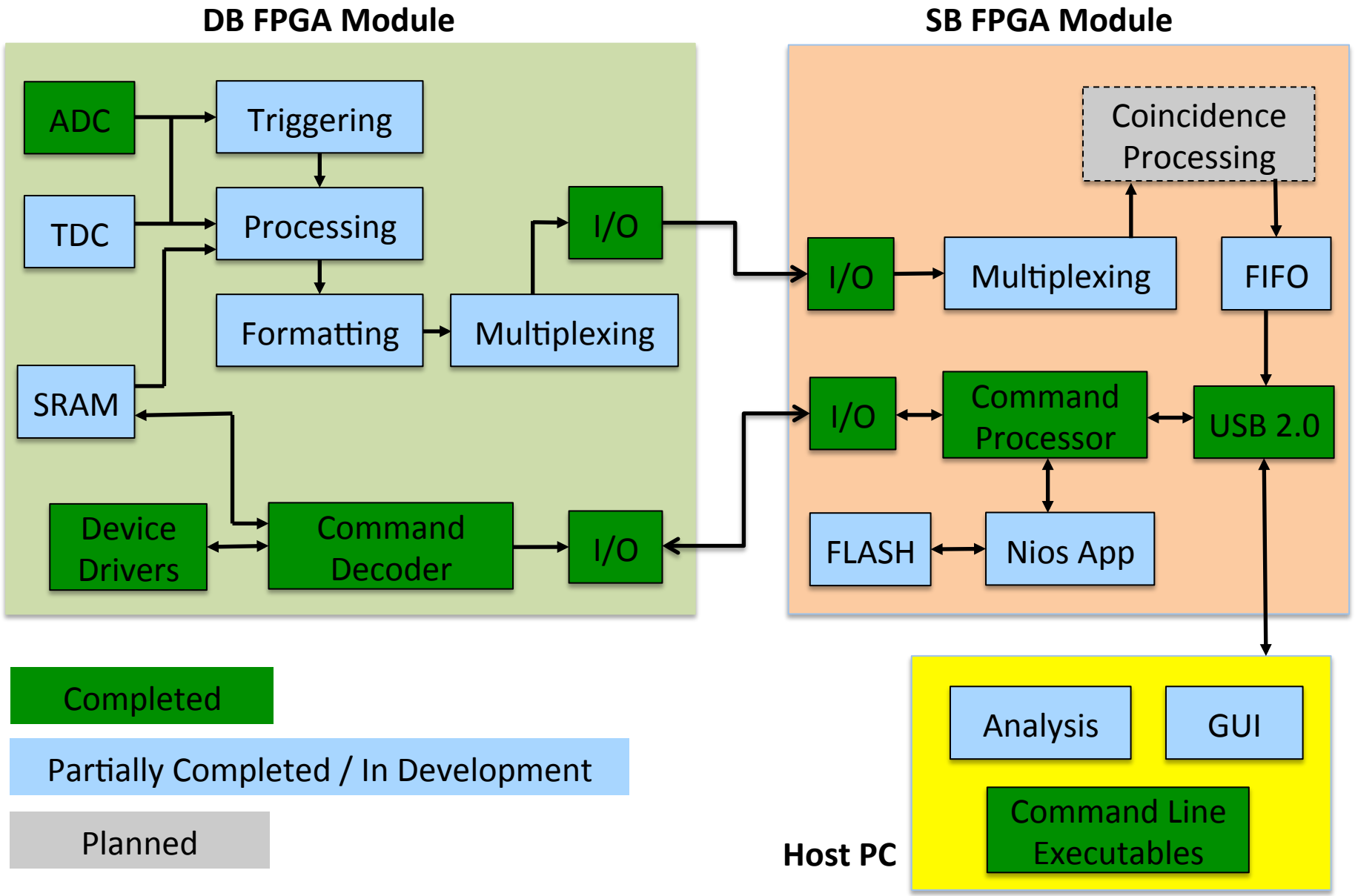
JTAG Connector

AS Mode Connector

External Clock Input

DIP Switch

Firmware / Software (v1.0)
"Oscilloscope" Mode for Small System

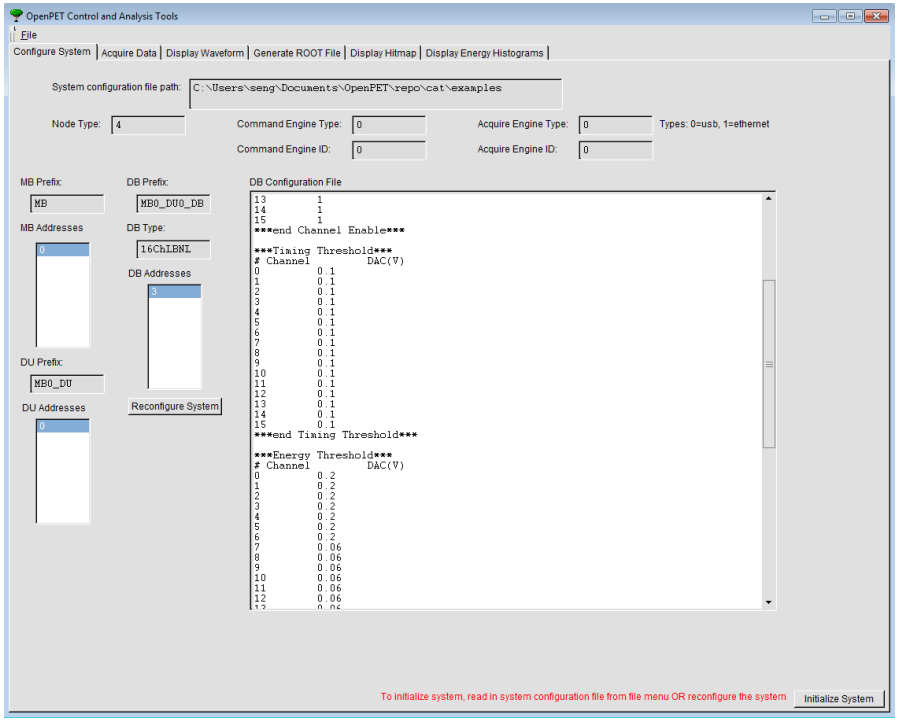


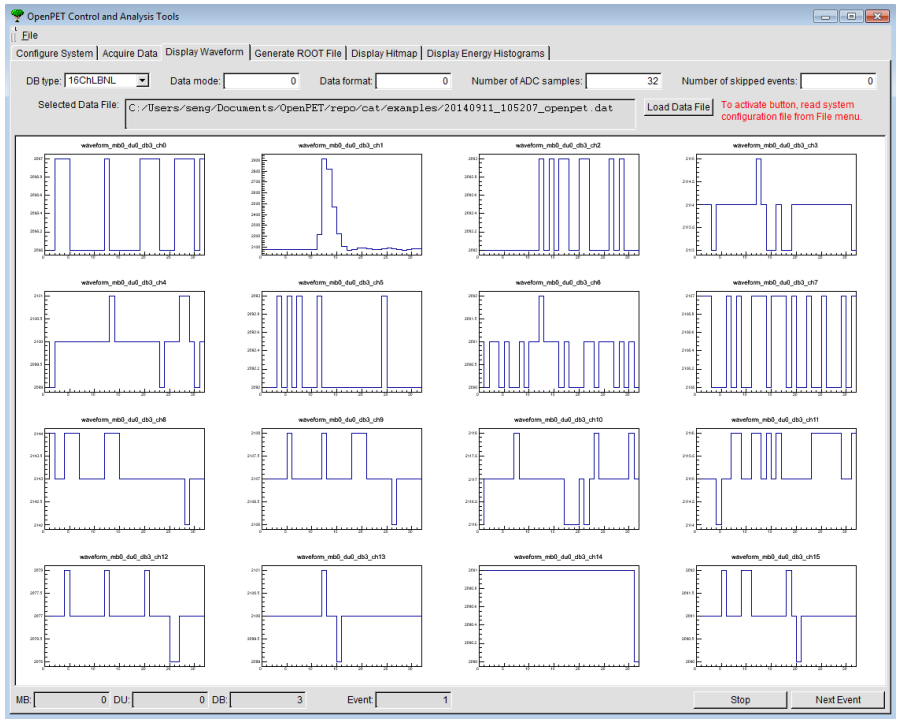
Firmware / Software (v1.0)

- Firmware on 16-Channel DB and SB to control the hardware and acquire “oscilloscope” mode data via USB (sampled waveforms are read out to be processed and analyzed offline) (see poster M11-27).
- Two command line executables
  1) opet_cmd_usb - control/configure the system.
  2) opet_acq_usb - acquire data.
- A User’s Guide (v1.0) is available for users to get started.
- All design files and sources are managed by a distributed version control system (Mercurial) hosted by Bitbucket, and also distributed through the OpenPET website.

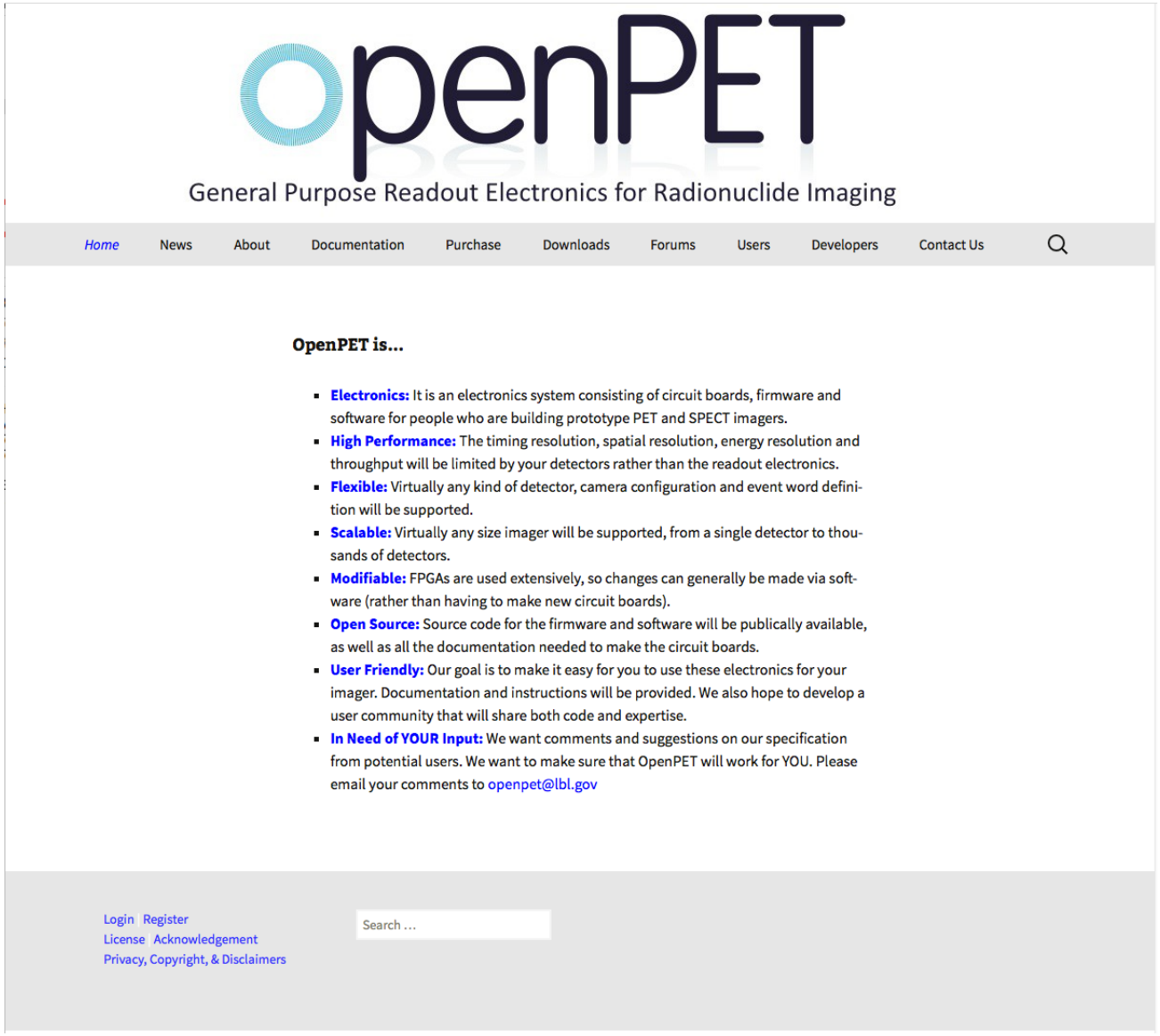
Control and Analysis Tools (CAT) v1.0

- An optional data acquisition and analysis software for the OpenPET electronics based on the ROOT framework.
- Macro or script files can be used to run the system.
- A GUI has also been developed to run the system.





OpenPET Website (openpet.lbl.gov)



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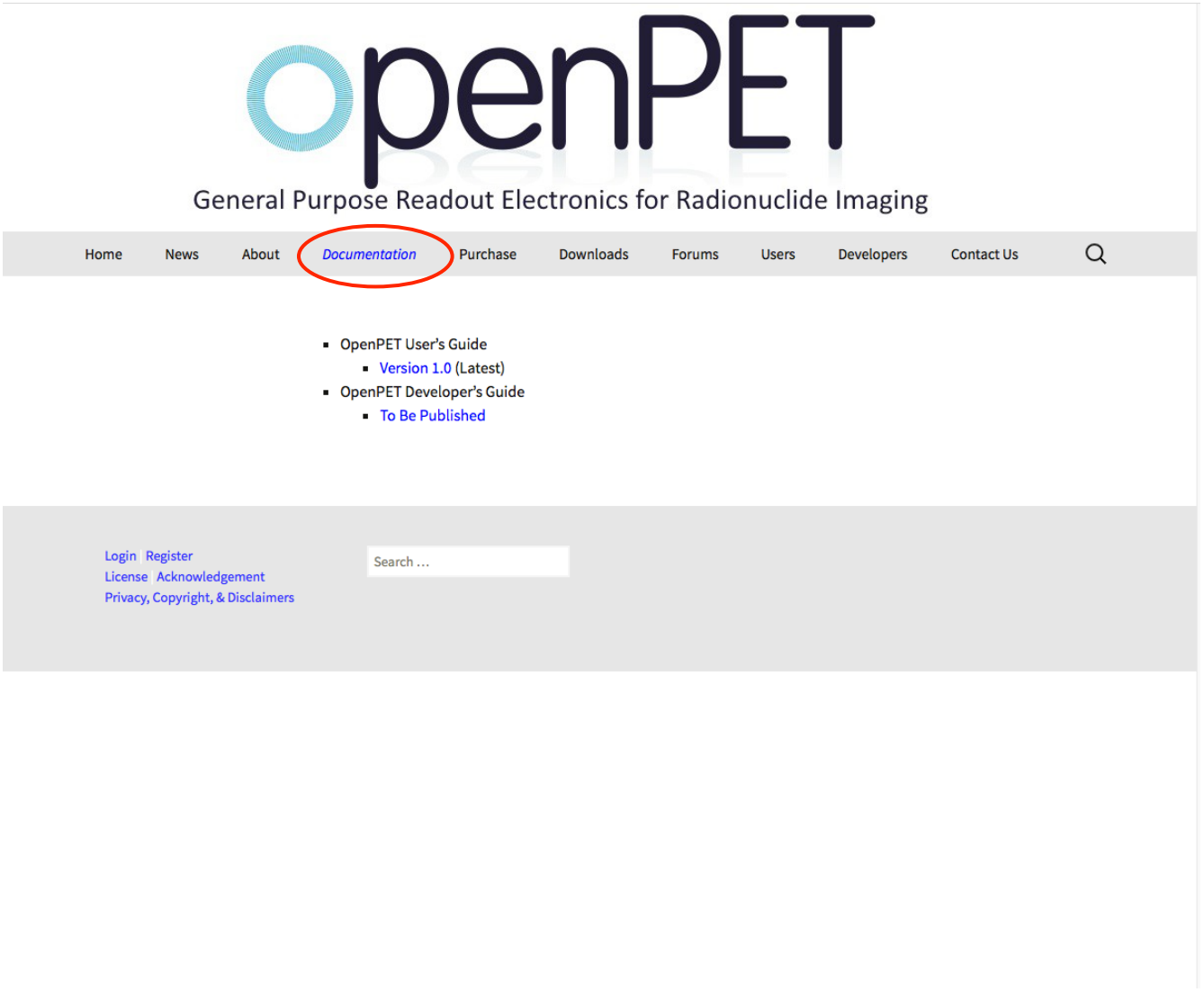

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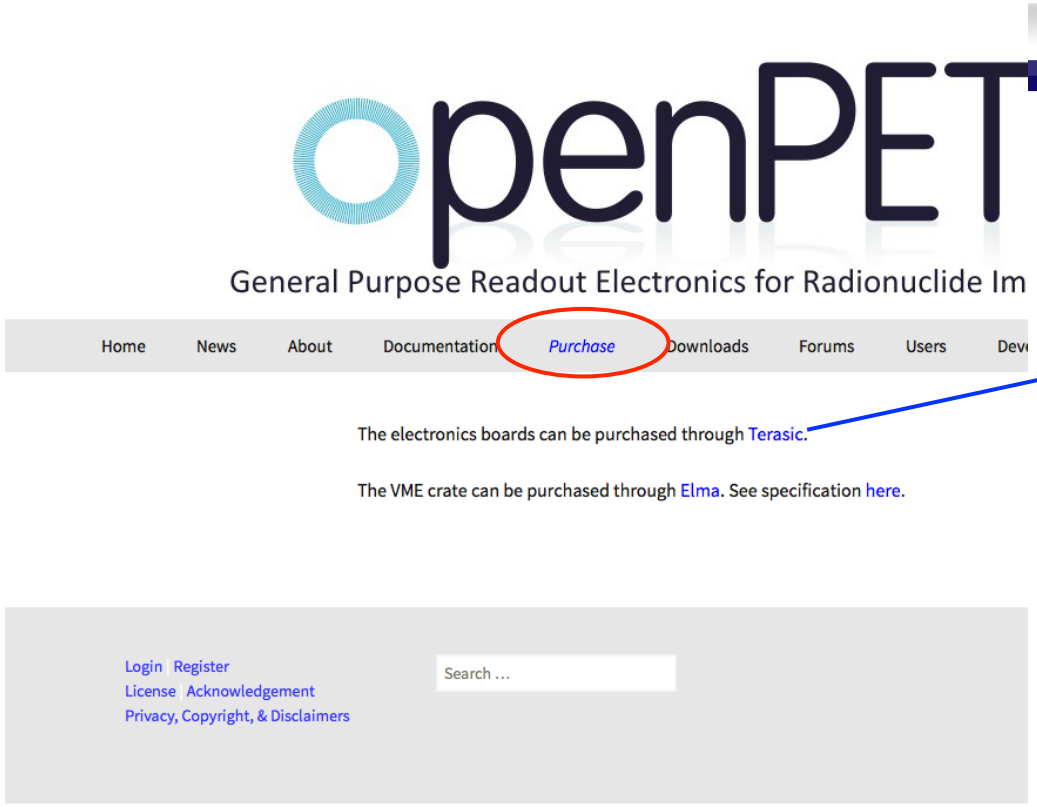

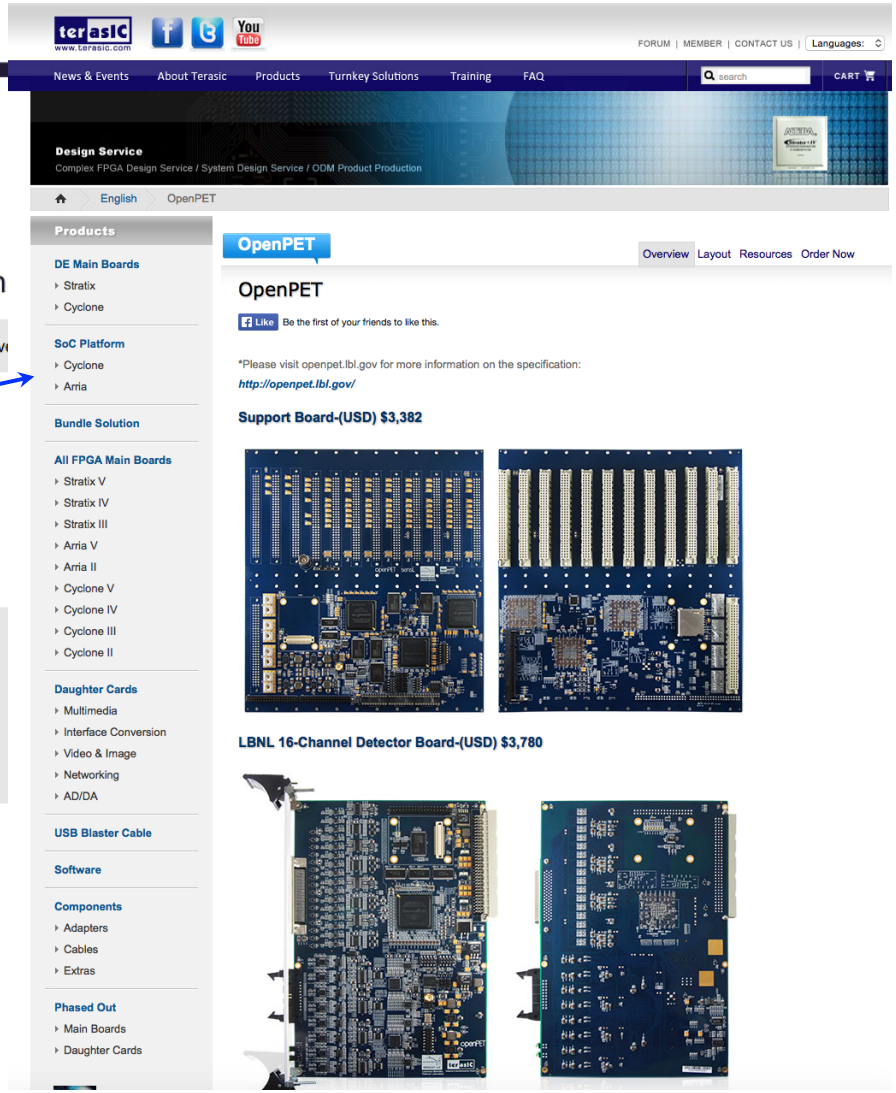

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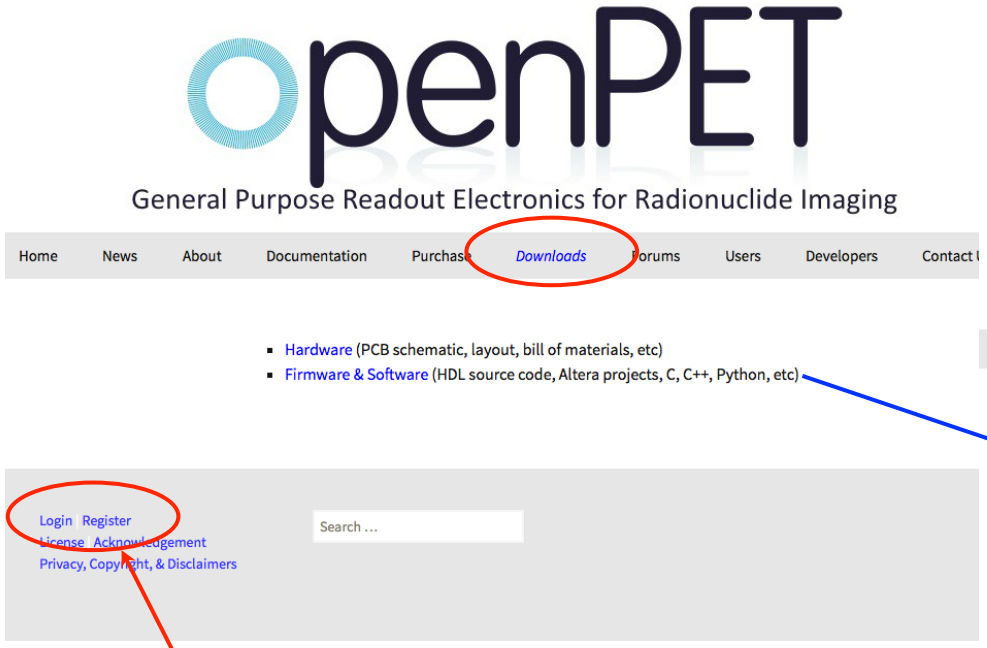
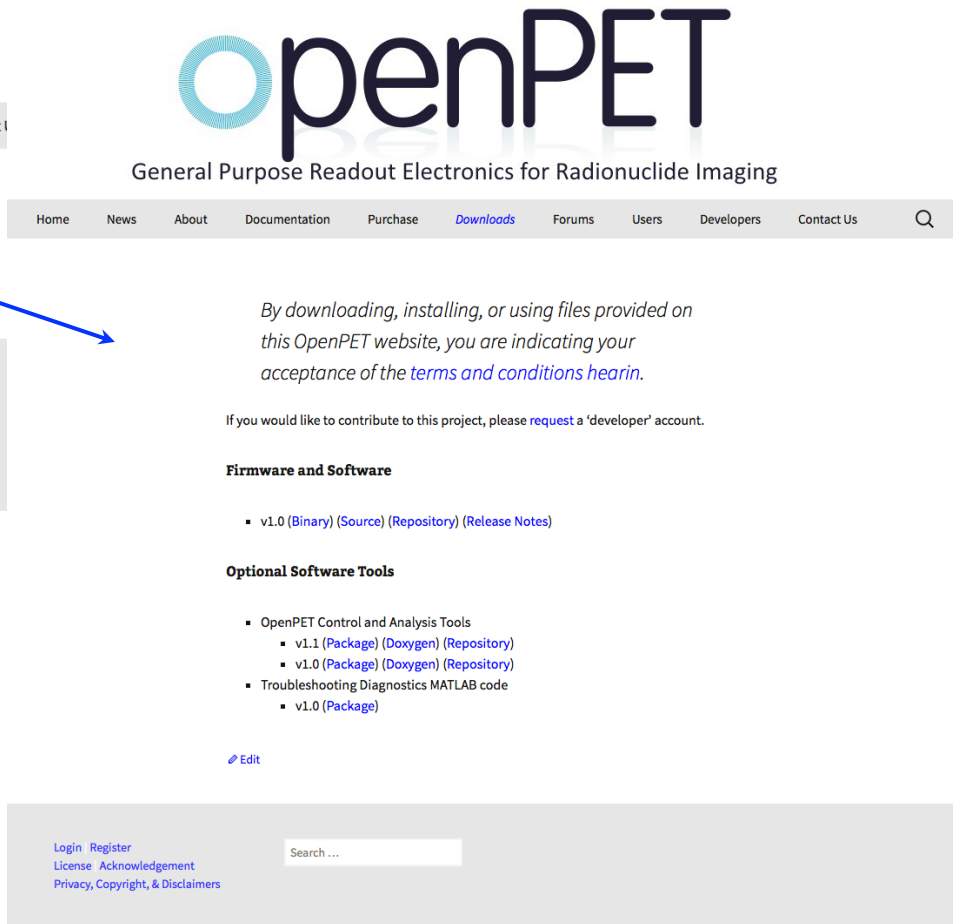


Must be registered and
login to view and download



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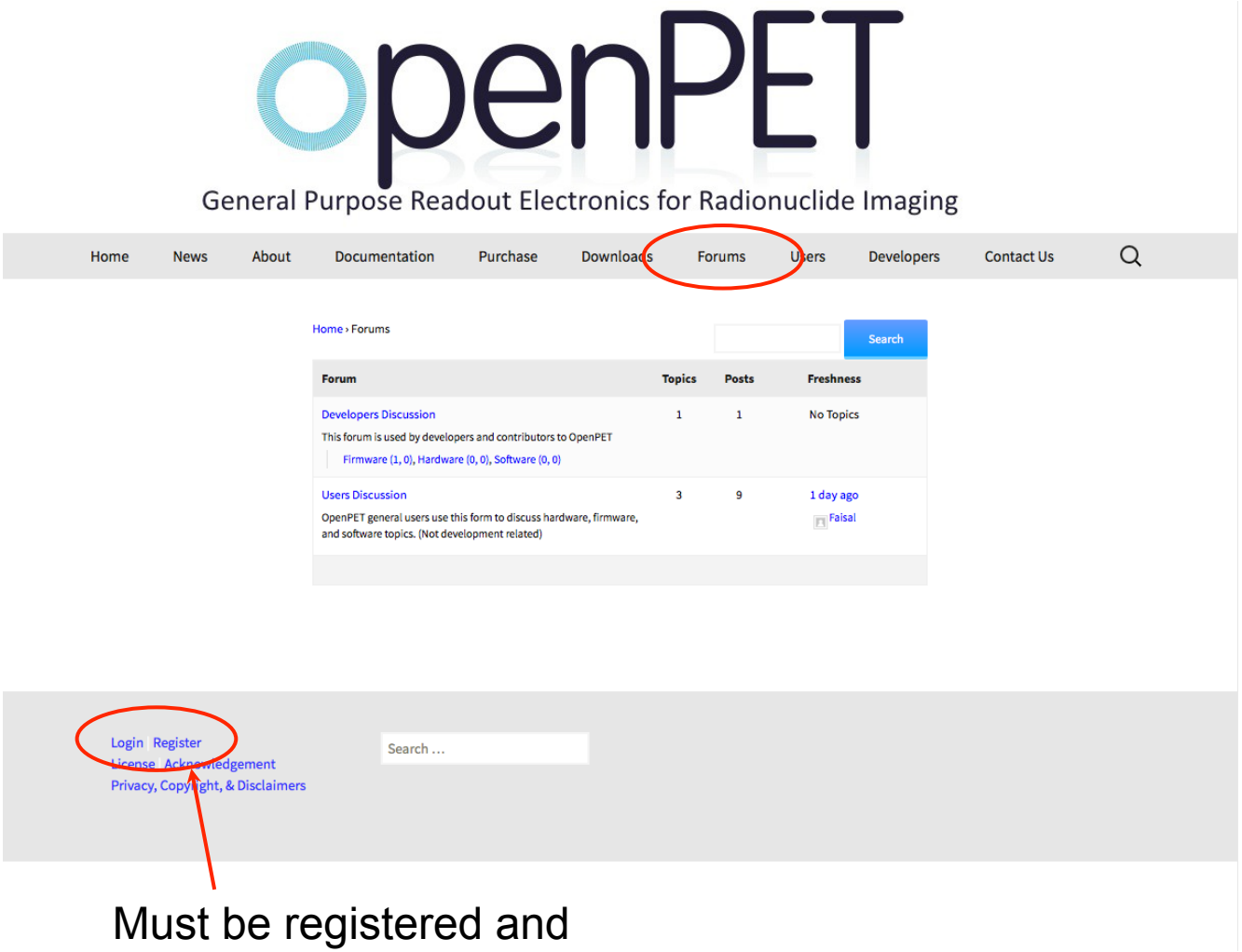
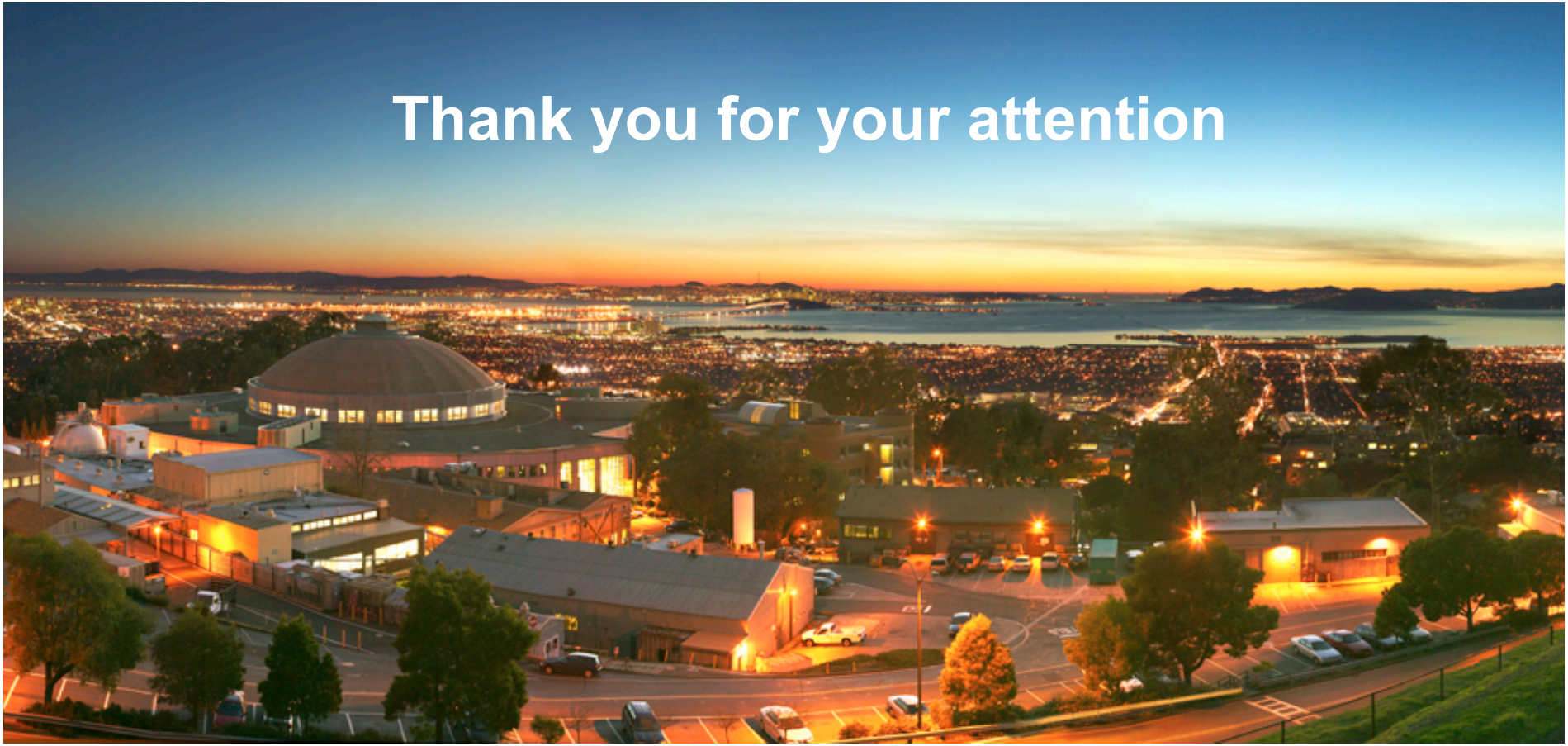


Must be registered and login to post and reply

Summary and Future Work

- Version 1.0 of the OpenPET electronics system has been released for users to get started.
- Electronics boards are available for purchase through Terasic.
- All design files, firmware, software are available for download through openpet.lbl.gov and also hosted in Bitbucket with Mercurial.
- A new improved website has been developed.
- Many shortcuts were taken in developing the firmware (v1.0), so we are going back to clean up and document the codes and improve on the firmware design. Additional firmware functionalities (SRAM lookup, singles event processing, high-performance TDC, etc) will be developed for upcoming releases.
- A User's Guide is available. Working on a Developer's Guide.
- Working on getting a Standard System started.
- An OpenPET lab will be set up at Berkeley in early 2015 to allow potential users to test and evaluate the OpenPET electronics before purchasing.
- A number of groups have adopted the OpenPET electronics in their projects and we will hear from them.

Go register at openpet.lbl.gov


Thank you for your attention

Progress towards the development of an OpenPET Based MRI Compatible PET Insert

M.S. Khan[1], E. Shams[2], L. Lamwertz[1], P. Kozlowski[3], F. Retiere[4], G. Schellenberg[5], V. Sossi[6], G. Stortz[6], J.D. Thiessen[7,8], C.J. Thompson[9] and A.L. Goertzen[2,5,8]

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[4]Detector Development Group, TRIUMF, Vancouver, Canada
[5]Department of Physics & Astronomy, University of Manitoba, Winnipeg, Canada
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[9]Montreal Neurological Institute, McGill University, Montreal, Canada

OpenPET Users Meeting, IEEE MIC 2014, Seattle, WA

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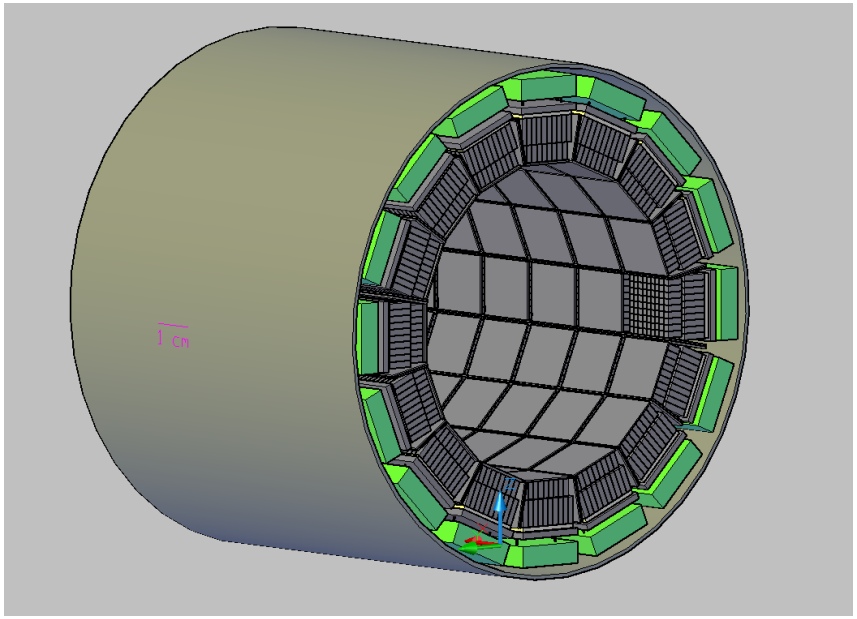
PET System Design Goals

- Fit within Bruker BGA12 gradient coil (114 mm diameter) for 7T MRI
- Axial FOV:
  - 1st generation: 2.5 cm
  - 2nd generation: 9 cm
- Transaxial FOV of 5.5 cm
- Spatial resolution:
  - 1st generation: < 1 mm
  - 2nd generation: < 0.75 mm
- Allow simultaneous PET & MR imaging



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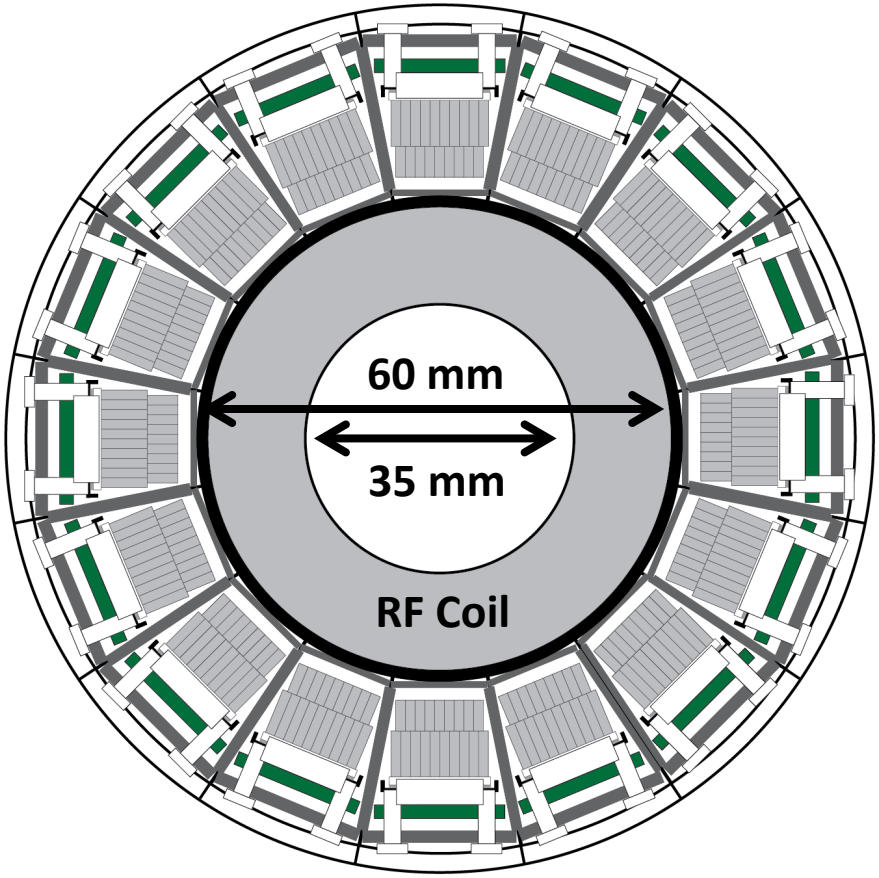
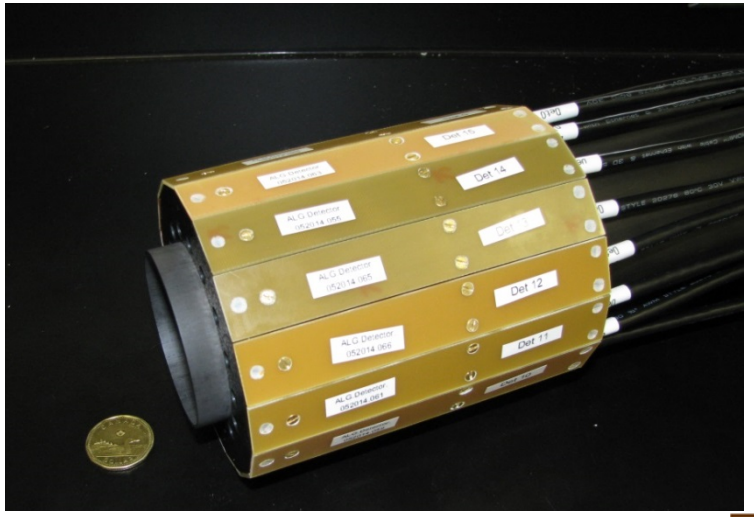
PET Ring Gantry





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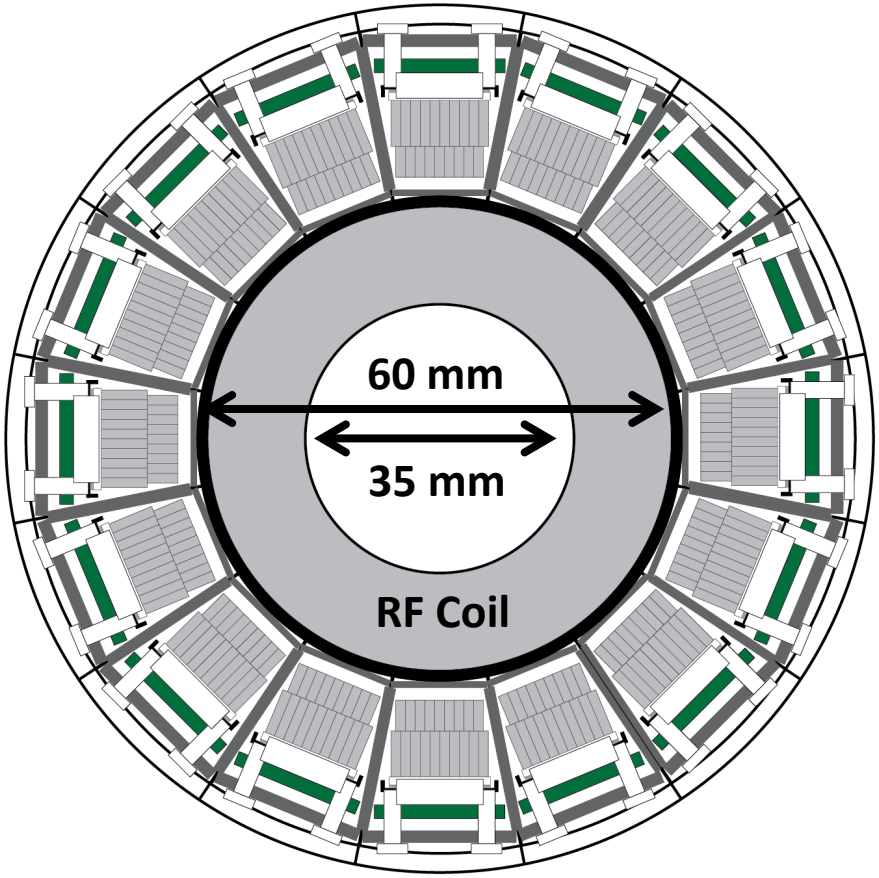
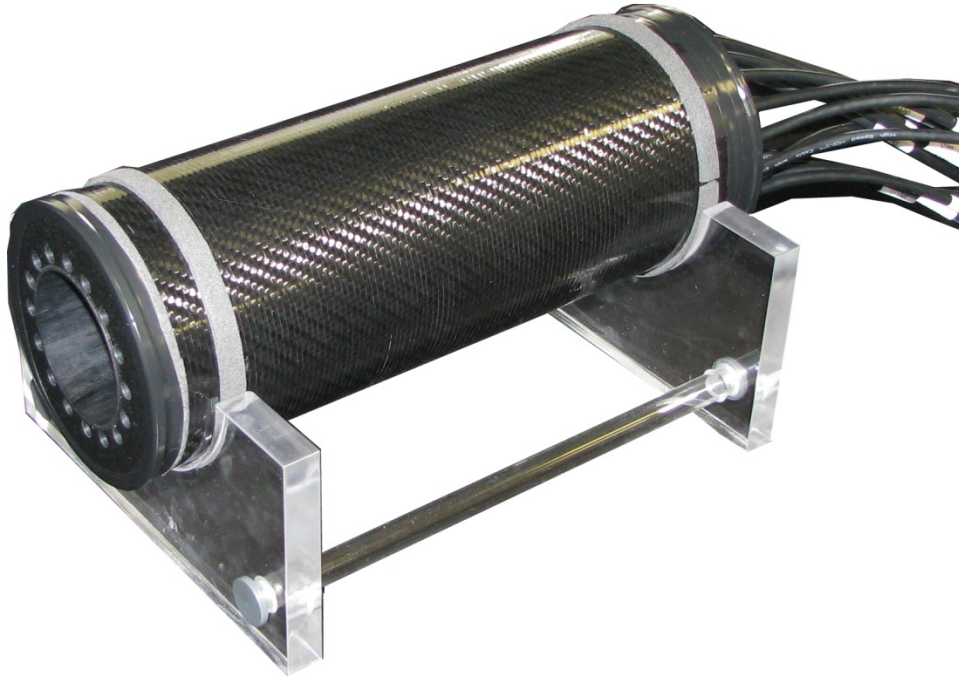
PET Ring Gantry





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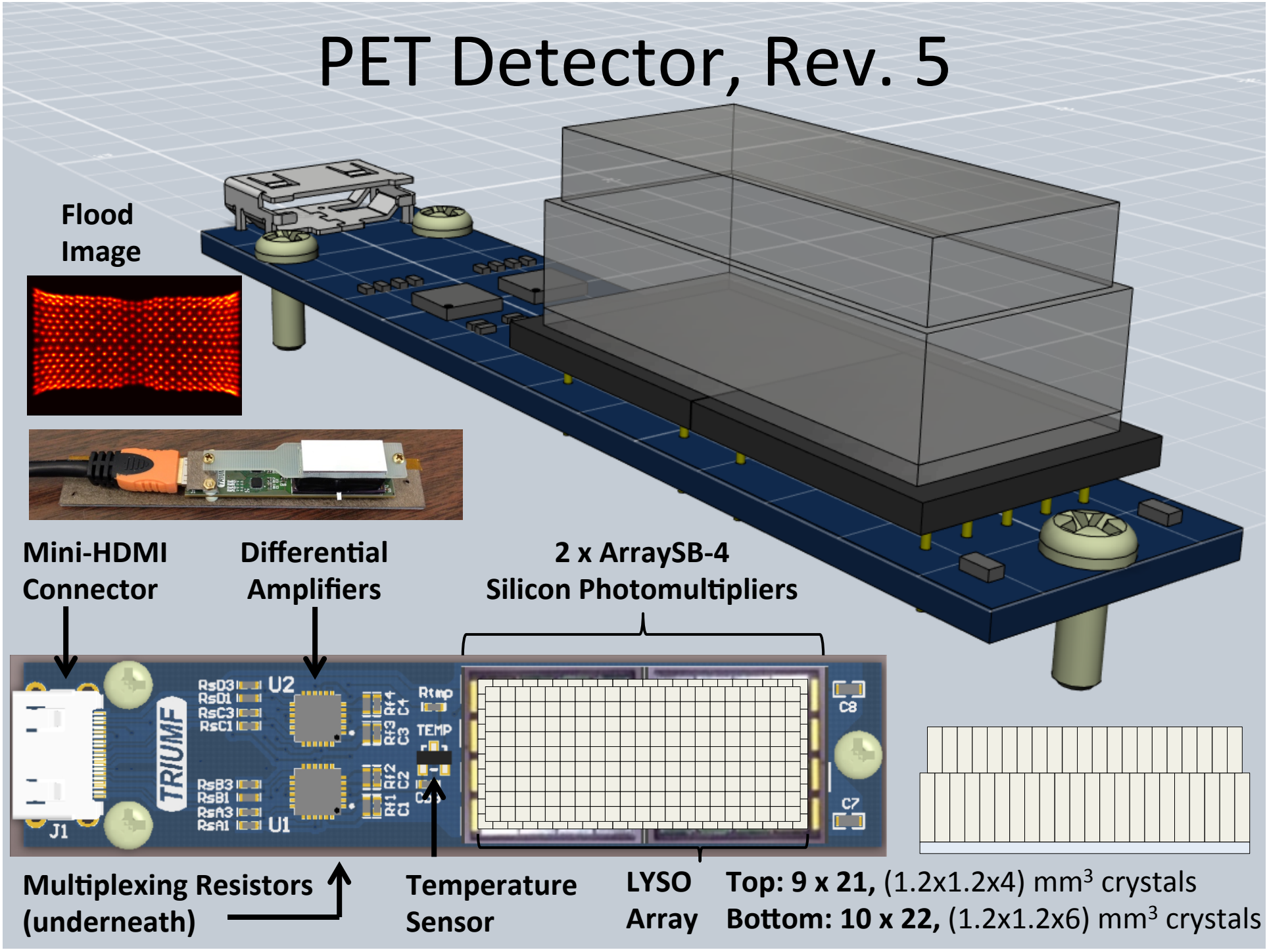
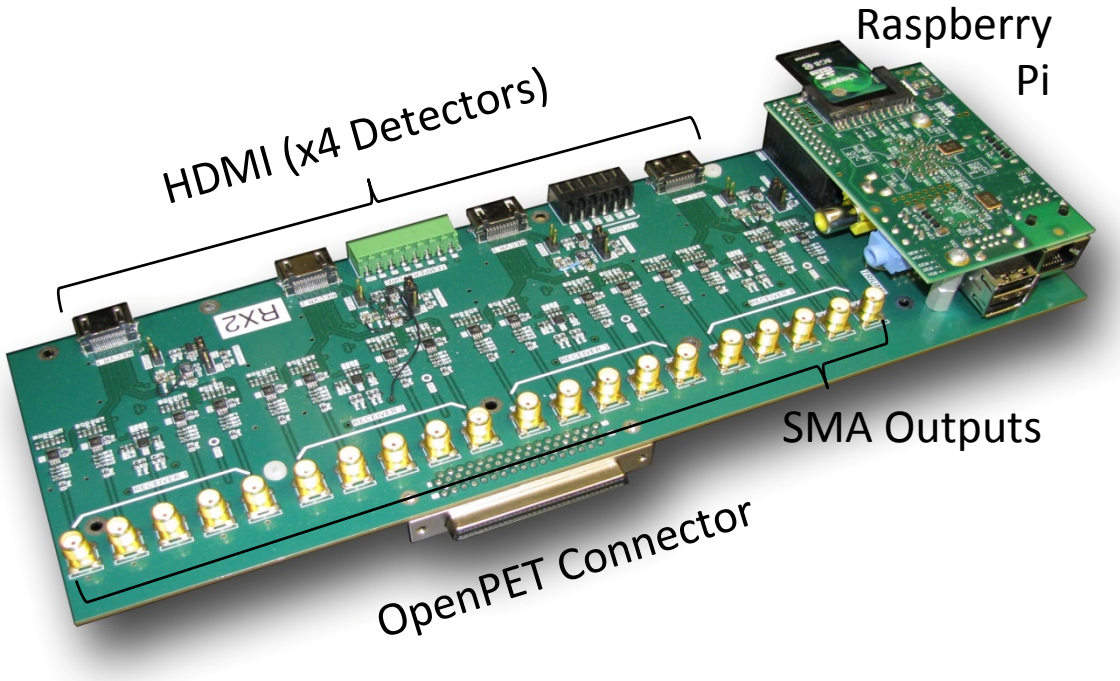
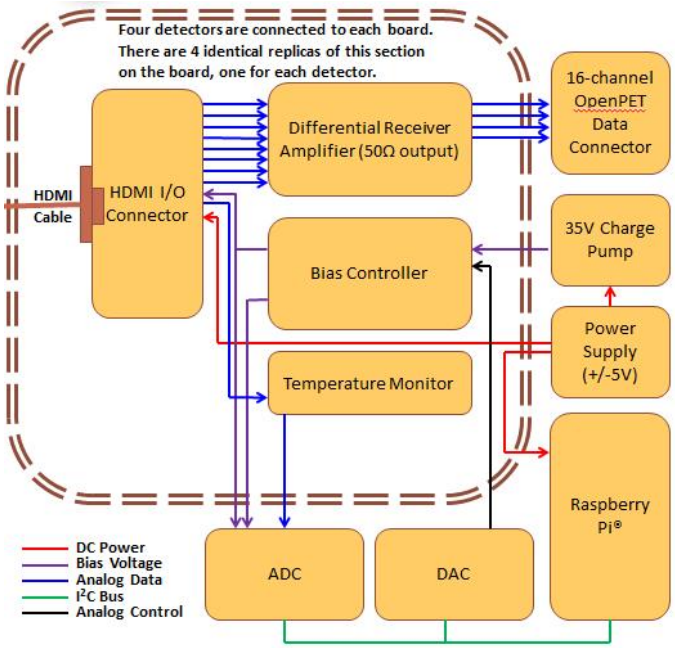
PET Detector, Rev. 5



Detector Interface Board/Slow Control System





- **Detector interface board** receives differential signals from HDMI-connected detectors and outputs single-ended signals via SMA or OpenPET connectors
- **Slow control system** manages low level functions of the PET system:
  - Controlling SiPM bias voltage and supplying detector power
  - Monitoring SiPM bias voltage and current
  - Monitoring and (maybe) controlling detector temperature

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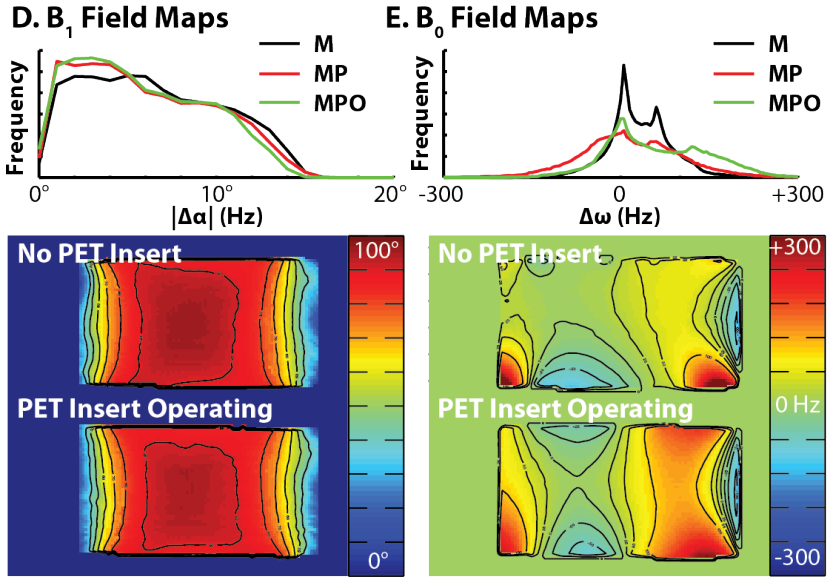
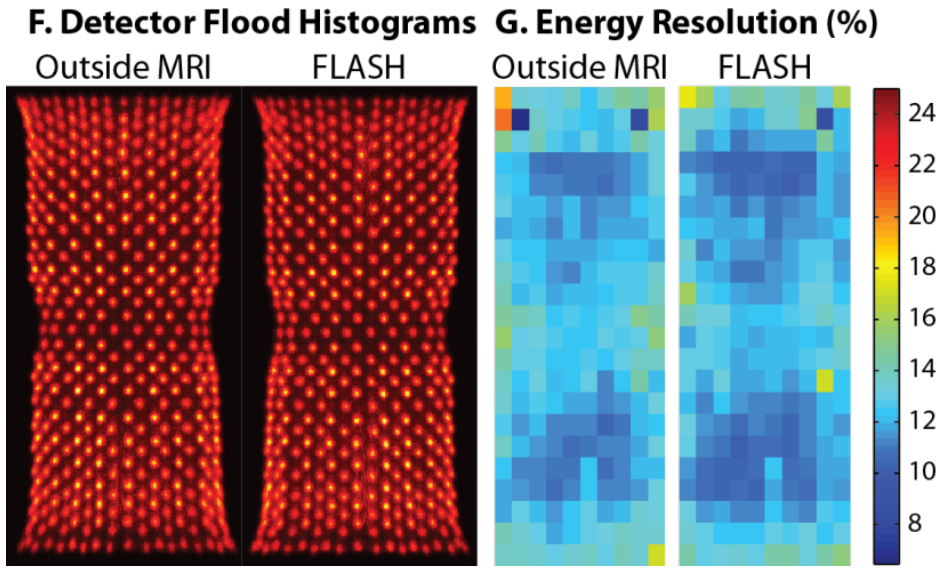
Shams *et al.*, M19-77

MR Compatibility Testing

C. MRI

SNR	M	MP	MPO	Image Homogeneity (%) M	MP	MPO
SE	148 ± 10	157 ± 6	154 ± 3	94.8 ± 0.3	94.5 ± 0.3	94.5 ± 0.3
RARE	250 ± 13	243 ± 13	250 ± 13	91.3 ± 0.9	90.0 ± 1.7	91.6 ± 0.6
FLASH	74 ± 2	75 ± 2	74 ± 2	88.3 ± 0.9	88.6 ± 0.7	88.2 ± 0.6
EPI	188 ± 4	159 ± 12	164 ± 9	40.6 ± 0.3	40.6 ± 0.1	40.6 ± 0.2





No significant impact on PET or MR performance seen in PET/MR testing.

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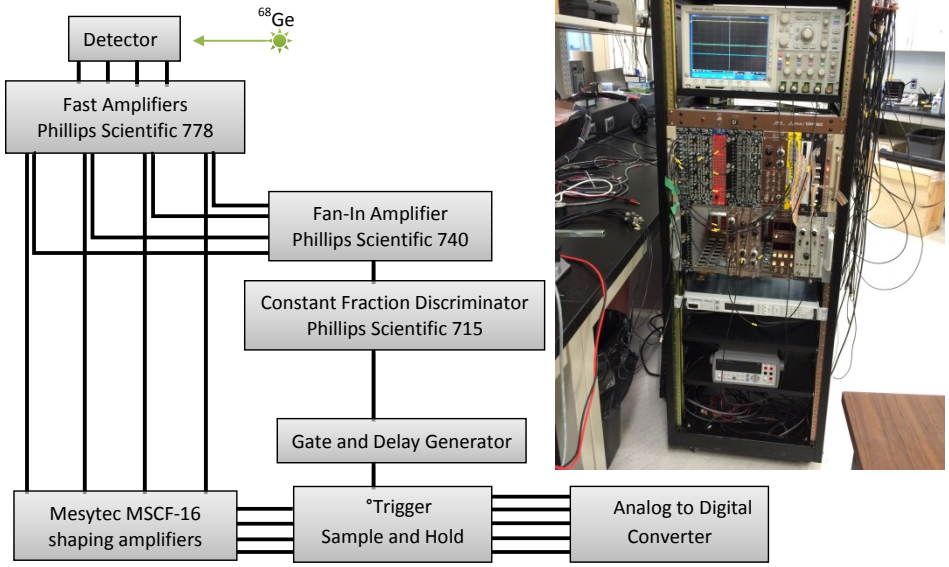
Progress with OpenPET

- Since the initial firmware release we have been using the oscilloscope mode to acquire initial data
- Created a Matlab GUI to facilitate running the OpenPET system
- Written custom C code to sort data files into format compatible with our analysis/sorting software
- Have successfully acquired data from 8 detectors using 2 detector boards simultaneously
  - Currently limited by fact that we only have 2 detector interface boards (2 more in production)

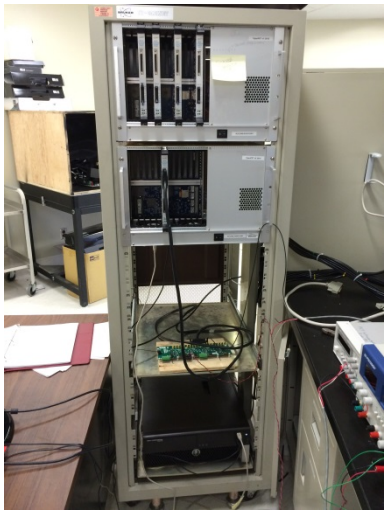
OpenPET vs. NIM Electronics Comparison

NIM



Liu and Goertzen, IEEE TNS, 61:35-43, 2014

OpenPET



- Oscilloscope mode capture
- 24-32 ADC samples acquired per trigger
- Energy for each channel taken as max ADC sample – 1 baseline value
- TDC values not currently used

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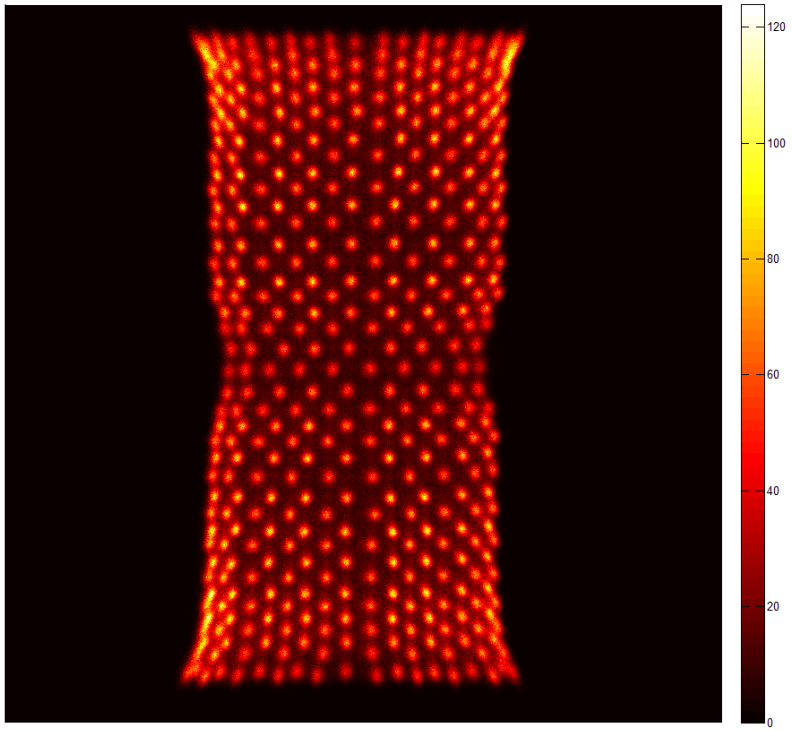
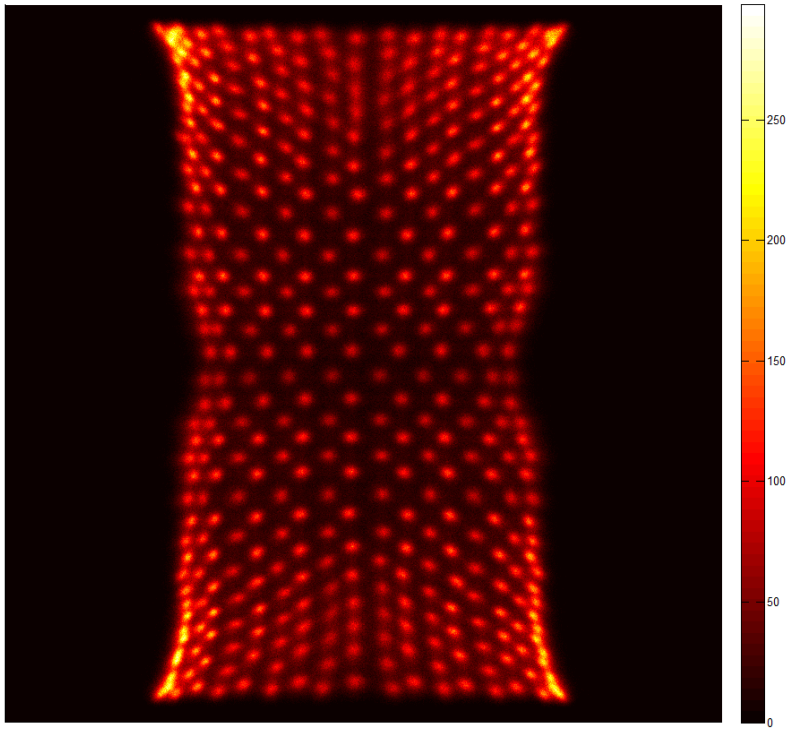
NIM vs OpenPET: Flood Images

NIM



OpenPET



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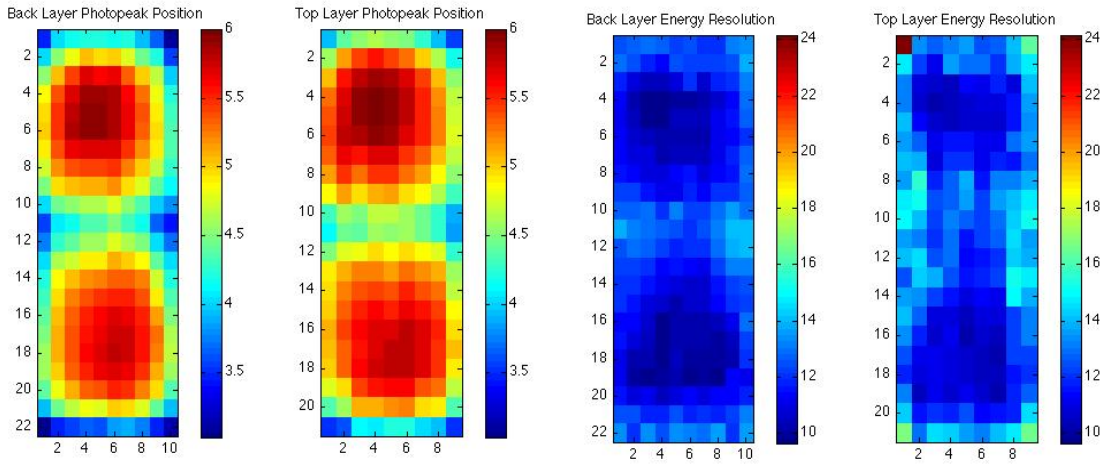
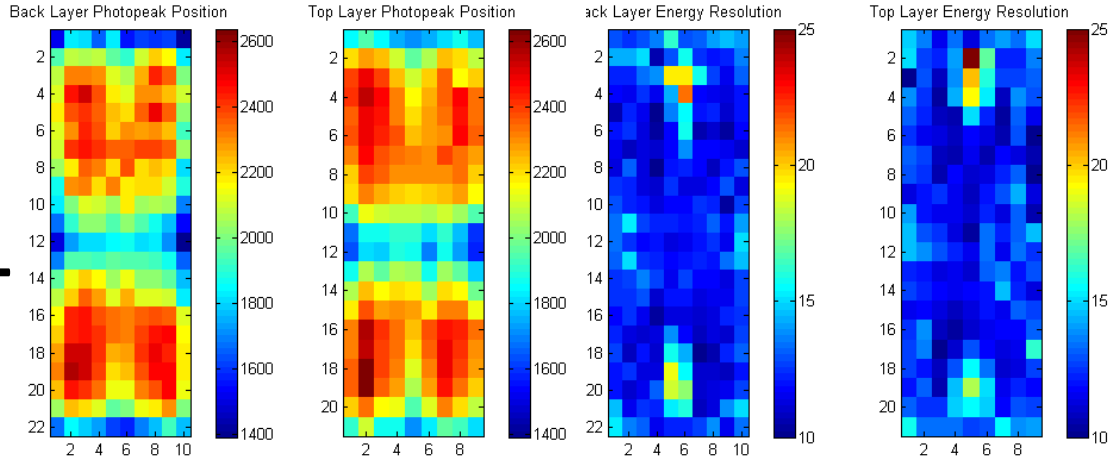
NIM vs. OpenPET: Energy Resolution

NIM



	Bottom Layer		Top Layer	
	Photopeak amplitude	Energy Resolution	Photopeak amplitude	Energy Resolution
Mean	4.84V	11.6%	5.08V	12.5%
St. Dev.	0.67V	1.1%	0.57V	1.7%
Max	5.93V	14.1%	6.00V	25.0%
Min	3.03V	9.6%	3.52V	10.2%

OpenPET



	Bottom Layer		Top Layer	
	Photopeak amplitude	Energy Resolution	Photopeak amplitude	Energy Resolution
Mean	2123	12.5%	2178	12.6%
St. Dev.	20	0.7%	28	1.1%
Max	2638	21.3%	2577	27.3%
Min	1572	9.9%	1391	8.4%

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Current Limitations

- Current implementation acquires 32 samples x 16 channels per trigger + TDC sample.
- Data packet size is 531 words x 4 bytes/word = 2124 bytes/event
  - 2 start words
  - 16 x 32 ADC sample words (512 ADC words)
  - 16 TDC sample words
  - 1 end word
- Maximum event rate over 40MB/s USB2 is ~18.8kcps @2.1 kB/event

OpenPET Firmware Development Focus

- The oscilloscope mode firmware allows for creating user defined oscilloscope modes.
- Over the next few months we plan to work within the framework of the oscilloscope mode to implement support for higher data rates in our system in a multi-step process.
- The key advantage to this approach is that we can completely recycle the existing oscilloscope mode event packager and commands

Step 1: 'Board level mode'

- We recognize that the only information we need for each channel is (max – baseline)
- In this mode, the data packet will consist of 35 words x 4 bytes/word = 140 bytes/event
  - 2 start words
  - 16 max – baseline values
  - 16 TDC samples
  - 1 end word
- Maximum event rate over 40MB/s USB2 is ~285 kcps @ 140 B/event

Step 2: 'Detector level mode'

- Each detector board supports 4 detectors, arranged as 4 groups of 4 channels/detector.
- In this mode, we will modify the event triggering so that a trigger only processes and packets data from the 4 channel group generating the event.
- The data packet will consist of 8 words x 4 bytes/word = 32 bytes/event
  - 2 start words
  - 4 max – baseline values
  - 1 TDC sample
  - 1 end word
- Maximum event rate over 40 MB/s USB2 is ~1.25 Mcps @ 32 B/event

Summary

- We have successfully used the OpenPET system to acquire data from 8 detectors simultaneously at an aggregate rate of ~15 kcps.
  - Flood image quality and overall performance is slightly degraded from NIM based acquisition, but will be suitable for our PET insert system.
- We have defined a plan to work within the existing oscilloscope framework to increase our event rate capability to 285 kcps in step 1 and 1.25 Mcps in step 2.

Our OpenPET Development Priority (i.e. 'Wish') List

- Time tag status words
  - Currently it is only possible to get coincidences for events from a single detector board due to the lack of global time stamps in the data stream
- Developer's Guide
  - Publishing this would be very helpful for allowing us to formalize code contributions

Acknowledgements

- Post-docs
  - Dr. Xuezhu Zhang (2011-2013, now at UC Davis)
  - Dr. Jonathan Thiessen (2012-2014, now at Lawson Health Research Institute, London, ON)
- Ph.D. Students
  - Dr. Fazal ur-Rehman, Physics & Astronomy (2008-2012, now at King Fahd University of Petroleum & Minerals, Saudi Arabia)
  - Bryan McIntosh, Physics & Astronomy (2012-2014, now at Cubresa, Inc.)
  - Mahmoud Al-Abedi, (2013-date), Biomedical Engineering
  - Muhammad Salman Khan (2013-date), Electrical Engineering
  - Greg Stortz, UBC Physics & Astronomy (2010-date)
- M.Sc. Students
  - Chen-Yi Liu , Physics & Astronomy (2010-2013, now at National University Singapore Medical School)
  - Leonid Lamwertz, Electrical Engineering (2011-2013, now at Westeel, Inc.)
  - Ehsan Shams, Biomedical Engineering (2013-date)
  - Graham Schellenberg, Physics & Astronomy (2013-date)
- Undergraduates
  - Eric Berg, Physics & Astronomy (2011-2012, now at UC Davis)
  - Megan McClarty, (not shown) (U of W Physics & Astronomy (2011, now at U of M ECE)
  - Barbara Angelucci (2014, Polytech Marseille)
  - Isabelle Delubac (2014, Polytech Marsille)
- Clinical Trials
  - Judy Patterson, Clinical Trials Coordinator, HSC

- Funding:
  - NSERC
  - University of Manitoba
  - Manitoba Health Research Council

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OpenPET for C-SPECT
a Cardiac SPECT/TCT Imaging System

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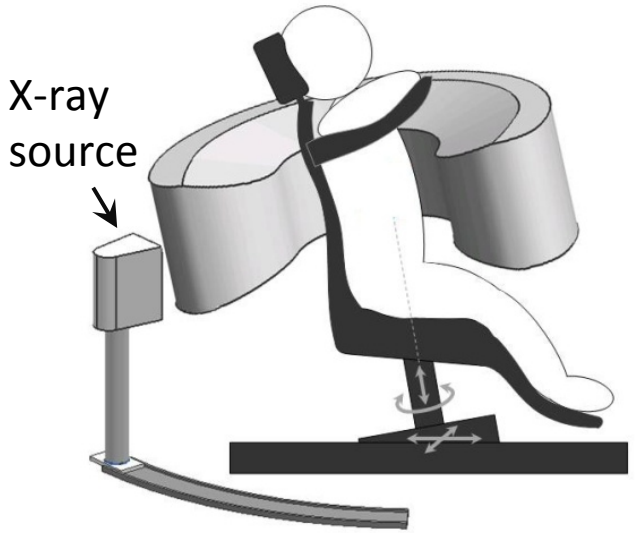
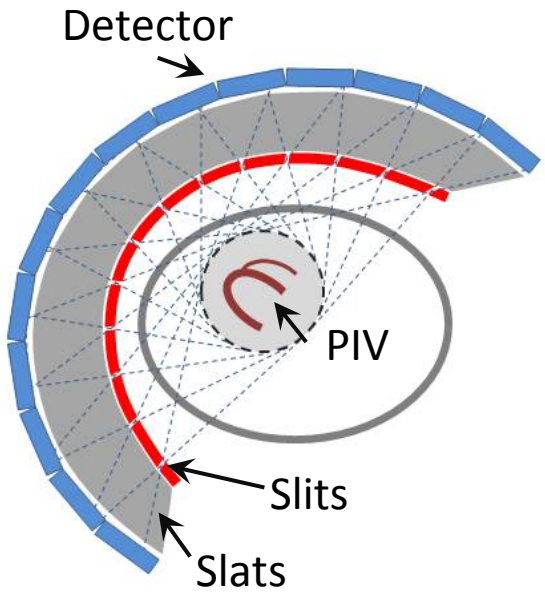
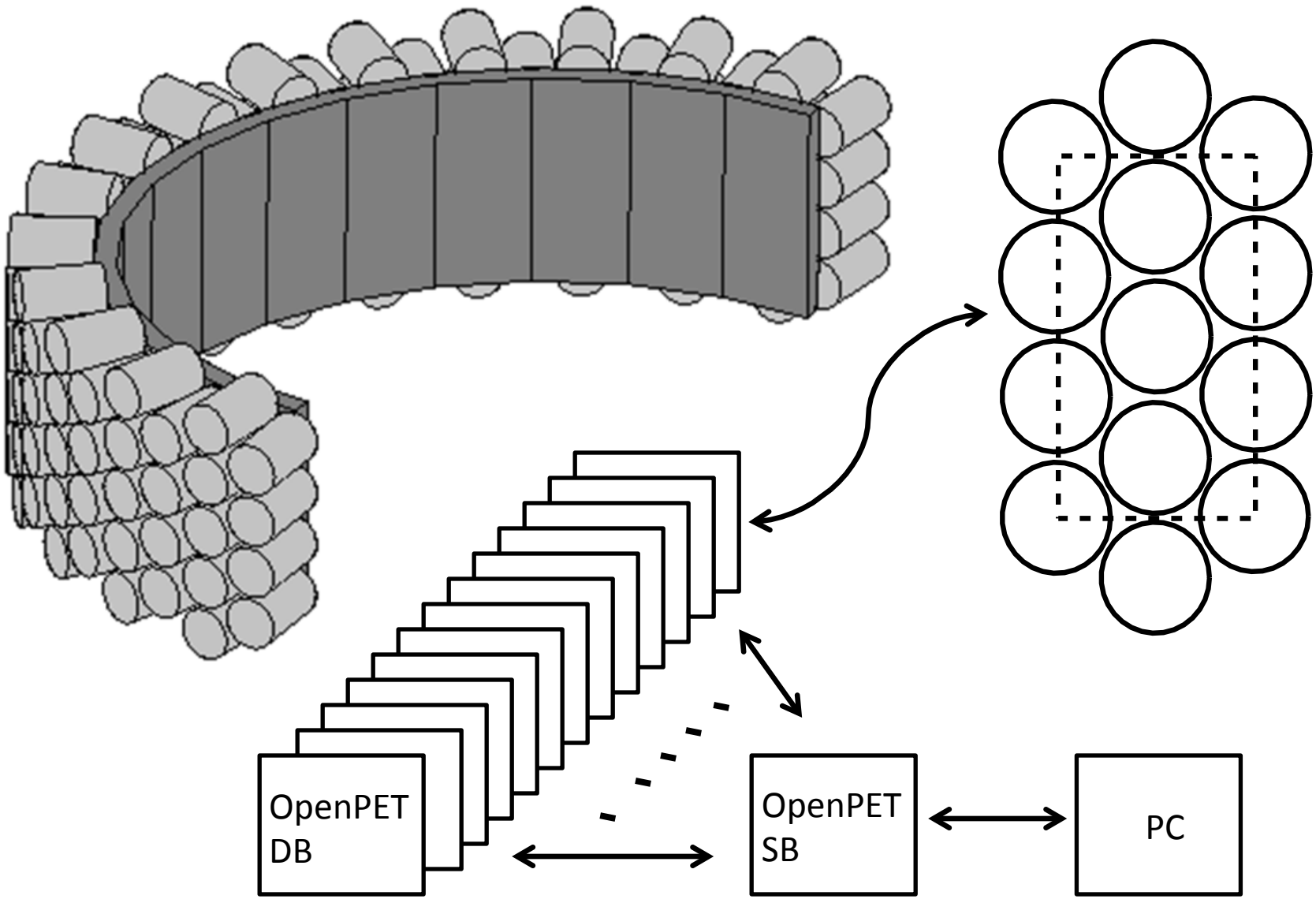
Our project

- C-SPECT: Dedicated, high performance cardiac SPECT/TCT platform
- Improve cardiac SPECT performance through sensitivity increase without resolution loss
- Large area curved NaI (Tl) detector focusing on a small cylindrical volume
  - 130 cm arc, 17 cm axial length
  - 14 modules (9.3x17 cm)
- High resolution: 2.5 mm pixel pitch
- Multiplex ratio = 217 pixel/PMT (2'')
- TCT with same detector requires high CR capability






OpenPET
DB
OpenPET
SB
PC

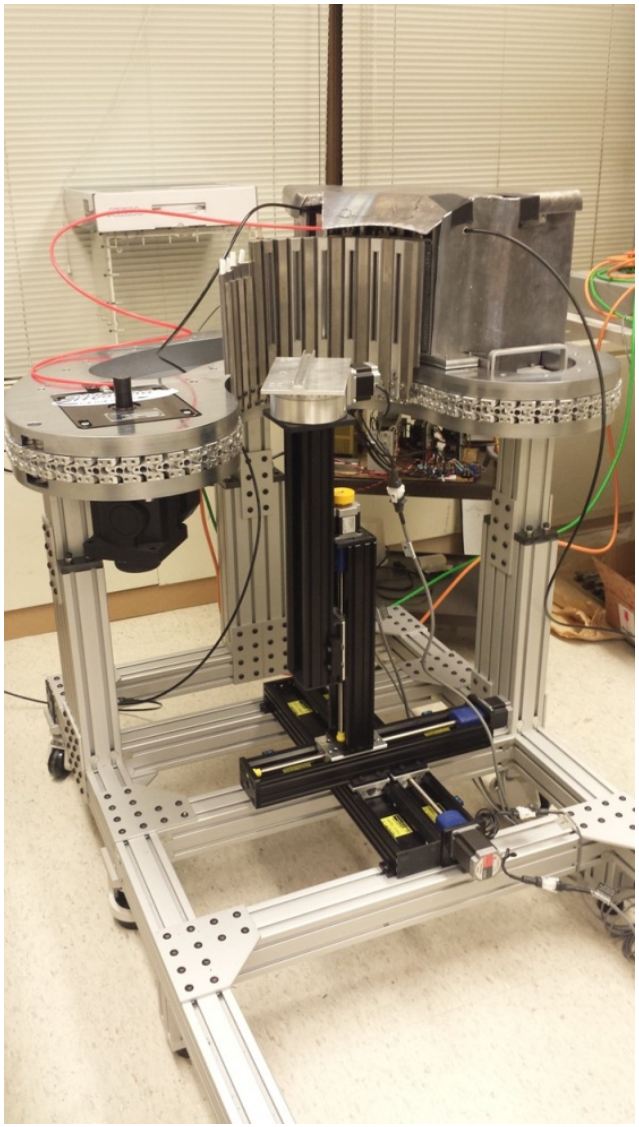
Our project, contn'd

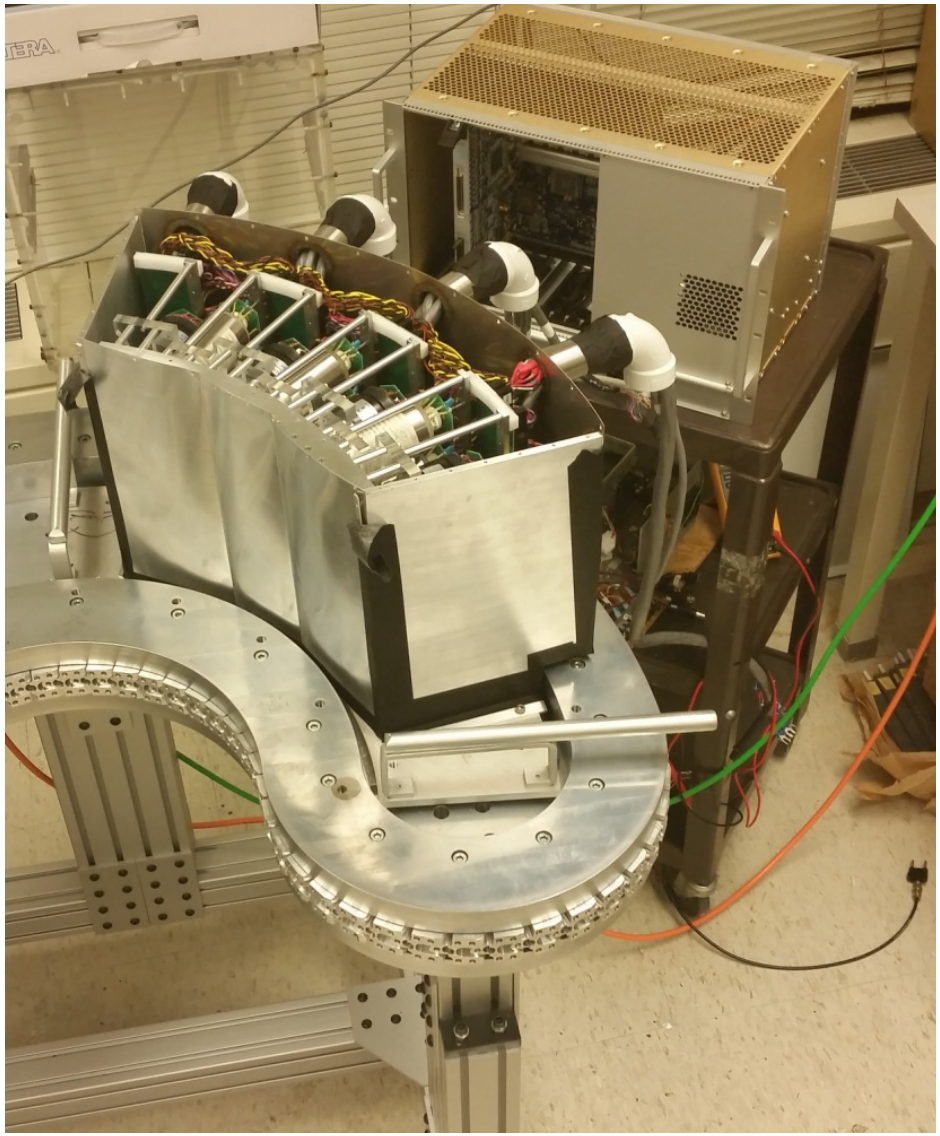
- System overview, Oral presentation **M17-1** , Friday 10:30am @6A - Michael Rozler
- Detector overview, poster presentation **M19-16**, Friday 2pm @4B - Kosta Popovic
- Interchangeable slit-slat collimator, poster presentation **M19-26**, Friday 2pm @4B - Sankar Poopalasingam

Why use OpenPET

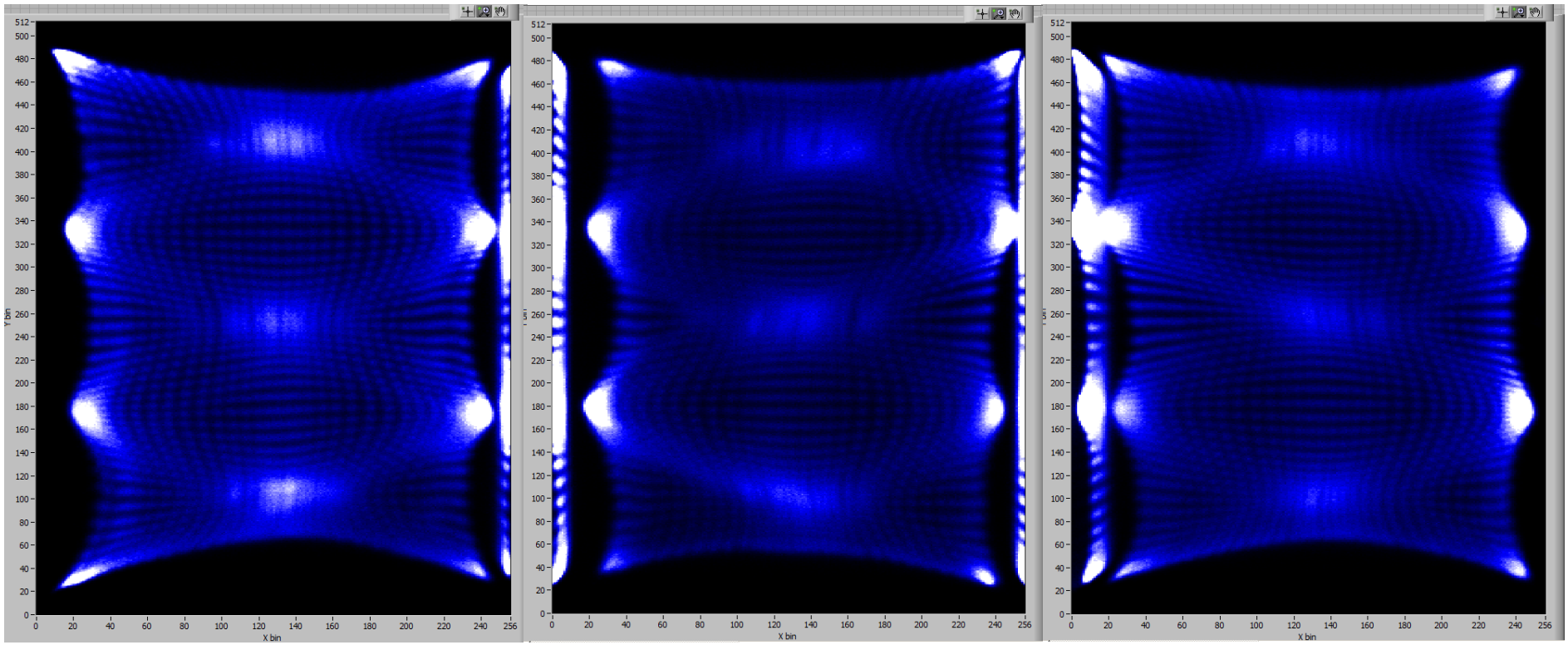
- Modular and scalable DAQ interface for NM R&D projects
- Performance capability fits our needs
  - Multi-module parallel operation
  - 40 MHz 12-bit ADC
- Good timing

C-SPECT status, Fall 2014
- 3-detector module -





Oscilloscope mode data



Decoding maps from the 3-detector module

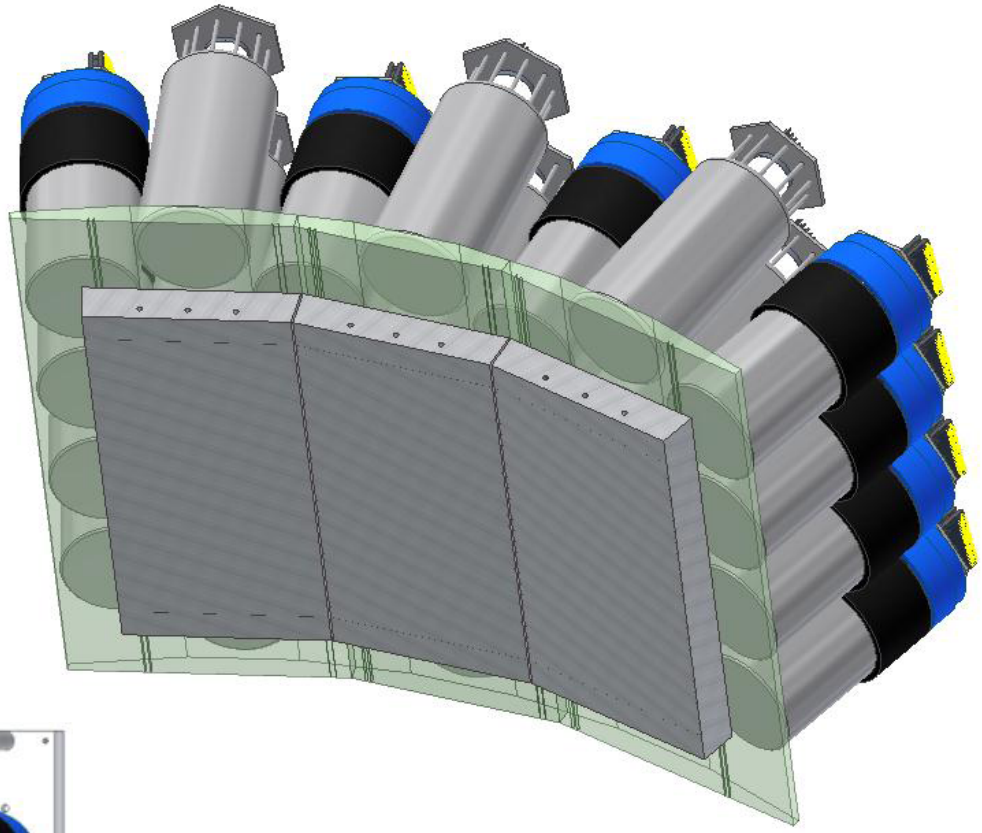
– Using native OpenPET firmware and code –

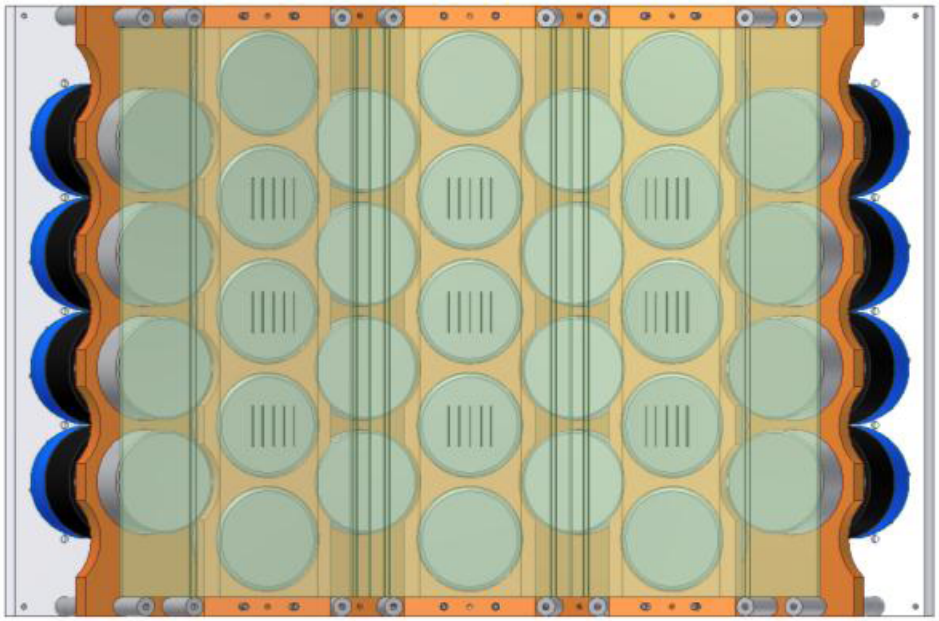
- Custom FPGA code to handle our system requirements (sum trigger, pixel ID, edge event module ID, variable event integration time for pileup correction (crucial for CT)…
- Expand to 14x 16ch DBs (… or 7x 32ch DBs)

Summary and Acknowledgements

- Promising early results with OpenPET DAQ and first release firmware/code
- Customizing FPGA code and ease of expansion of the DAQ will accelerate our imaging system development and translation to actual clinical studies
- Thanks to Seng, Qiyu and Faisal for help on setting up the system at Rush, and continued support in troubleshooting the OpenPET utilization in our SPECT/TCT system

Questions and Comments





OpenPET User Meeting
UC-Davis experience

Martin S. Judenhofer, PhD

Department of Biomedical Engineering, University of California-Davis, Davis, CA

OpenPET User Meeting, IEEE MIC Seatle, Nov 13, 2014

UC DAVIS
UNIVERSITY OF CALIFORNIA

cmg

Projects at UC-Davis Interested in OpenPET

- Small animal PET systems
  - High resolution brain PET
  - PET/MRI system

~ 64 detector modules
Using dual ended DOI

- Breast PET/CT Systems

~ 100 detector modules
Using dual ended DOI

- Explorer Scanner

~ 1900 detector modules
TOF capable
Single ended DOI
Operation in single mode

Equipment at UC Davis

Detector board (DB)

Support board in crate (SB)

Initially Performed Tests

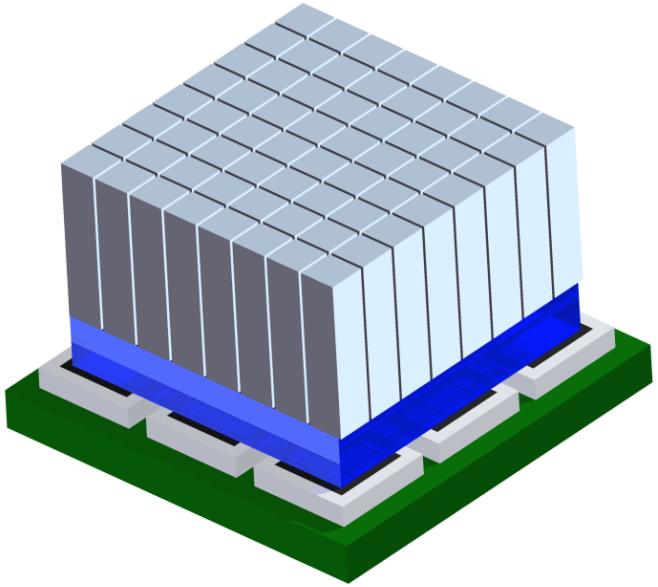
All tests are done using 16-channel oscilloscope mode

- Tests with pulse generator
  - Get familiar with system
  - Investigate system linearity and channel variation

- ADC linearity is excellent !
- < 1% variation across channels
- System responds as expected.

Further Tests with Block Detector

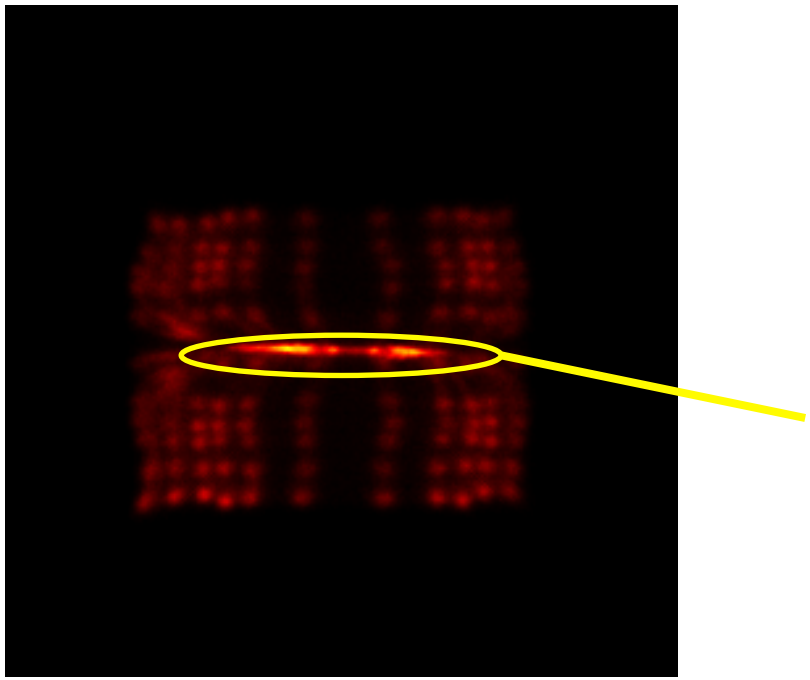
- Test with a 4-channle anger readout detector (SiPM based)
  - 8x8 LSO array (1.5x1.5x6mm^3)
  - 3x3 SiPM array (3x3 mm^2)
  - 4 channel ABCD
  - 1 fast timing channel



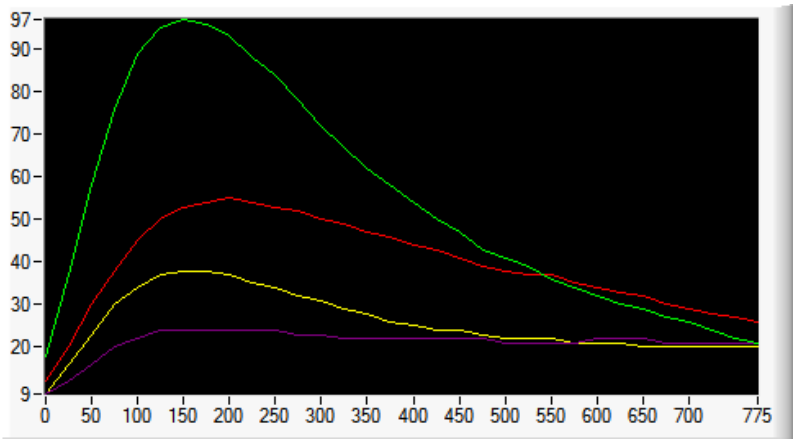
  - Acquire flood histograms
  - Investigate trigger schemes

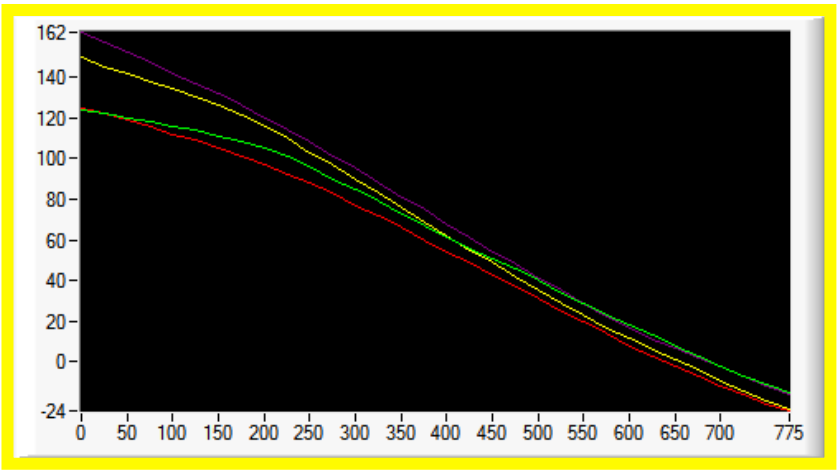
Results (Block Detector)

Inconsistent triggering was observed leading to artifacts in floods



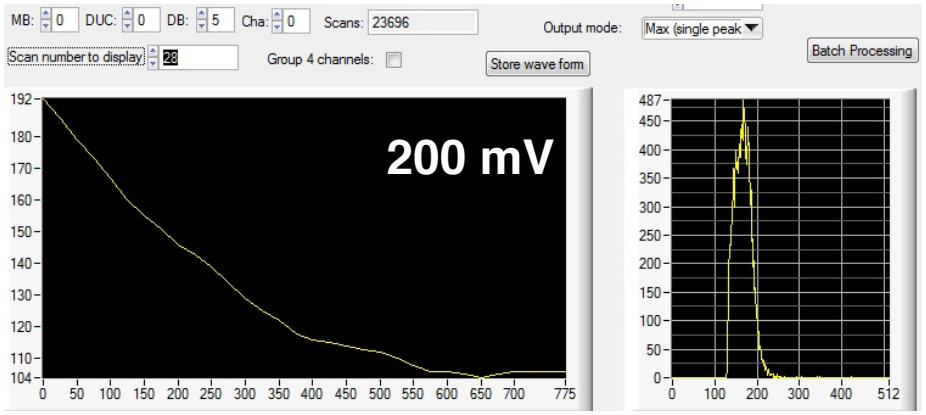
Artifact at center related to bad trigger events

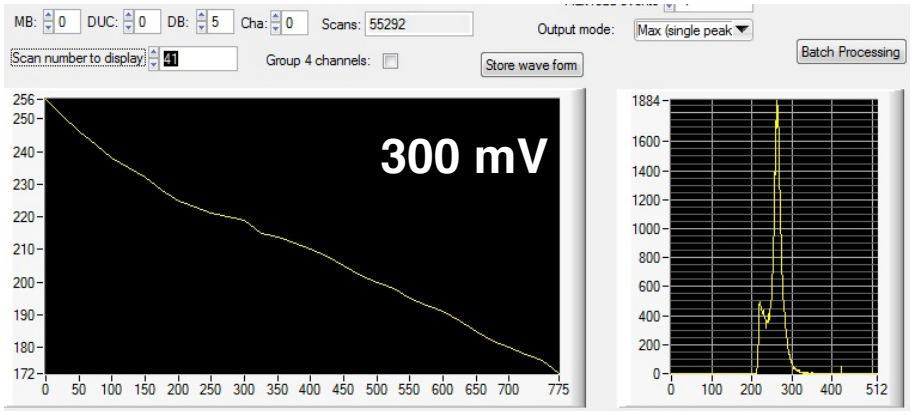


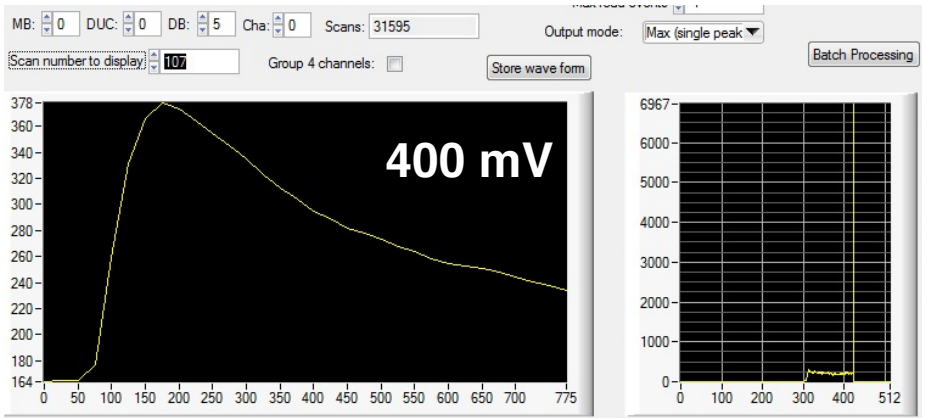


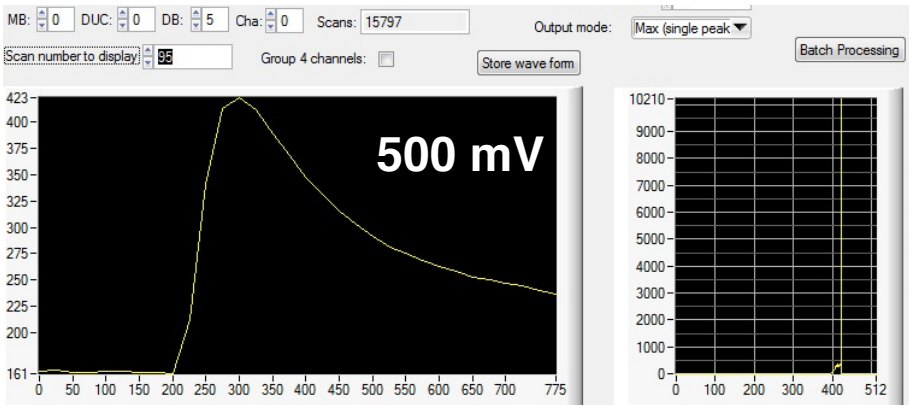
Results (Block Detector)

Inconsistent triggering depends on trigger threshold and pulse length



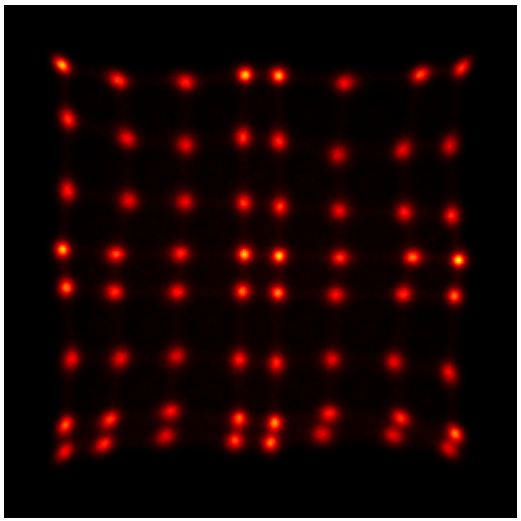




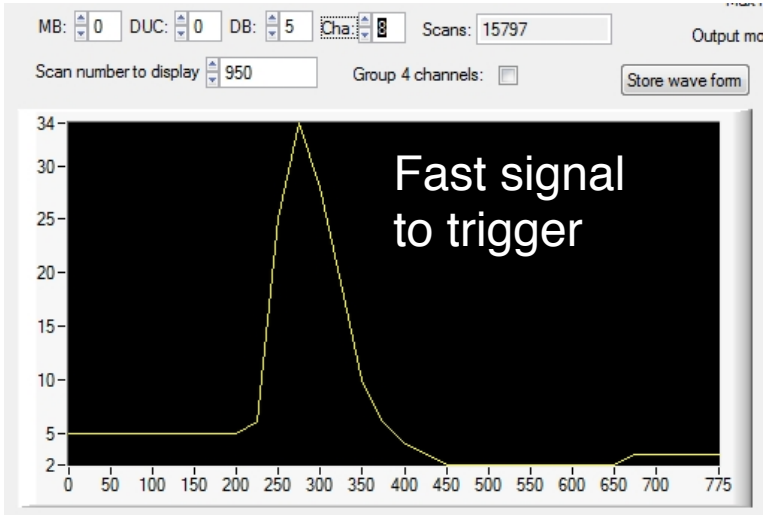


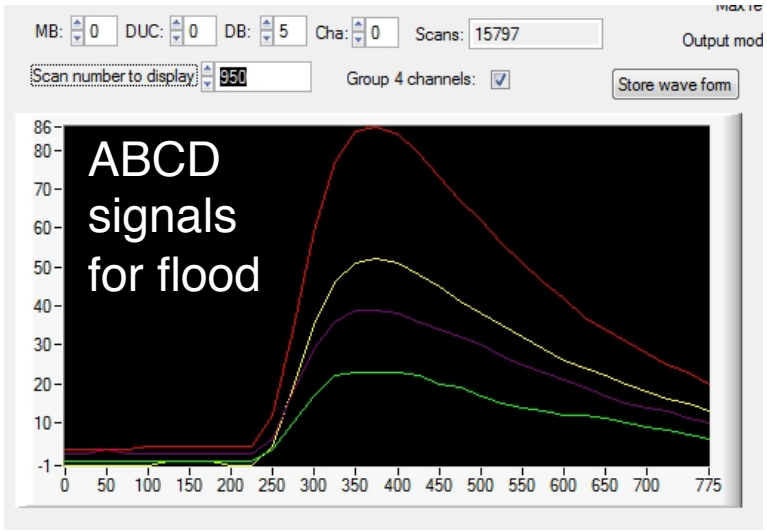
Results (Block Detector)

Consistent triggering using fast timing signal



1800 sec acquisition





Next Steps and Wish-list

- Resolve triggering issue to acquire consistent data
- Features to reduce data size (increase bandwidth)
  - Add option to select number of channels to be acquired in oscilloscope mode
  - Provide single event mode with onboard X/Y and Energy calculation
- Implement CFD with ~ 500ps resolution

Thanks for your attention…